On intraseasonal to interannual time scales, the climate of the United States is strongly affected by modes of atmospheric circulation variability like the North Atlantic Oscillation (NAO)/Northern Annular Mode (NAM), North Pacific Oscillation (NPO), and Pacific/North American Pattern (PNA).[7, 8, 9] These modes are closely linked to other atmospheric circulation phenomena like blocking and quasi-stationary wave patterns and jet streams that can lead to weather and climate extremes.[10] On an interannual time scale, coupled atmosphere–ocean phenomena like El Niño–Southern Oscillation (ENSO) have a prominent effect.[11] On longer time scales, U.S. climate anomalies are linked to slow variations of sea surface temperature related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO).[12, 13, 14]

These modes of variability can affect the local-to-regional climate response to external forcing in various ways. The climate response may be altered by the forced response of these existing, recurring modes of variability.[15] Further, the structure and strength of regional temperature and precipitation impacts of these recurring modes of variability may be modified due to a change in the background climate.[16] Modes of internal variability of the climate system also contribute to observed decadal and multidecadal temperature and precipitation trends on local to regional scales, masking possible systematic changes due to an anthropogenic influence.[17] However, there are still large uncertainties in our understanding of the impact of human-induced climate change on atmospheric circulation.[4, 18] Furthermore, the confidence in any specific projected change in ENSO variability in the 21st century remains *low*.[19]

5.2 Modes of Variability: Past and Projected Changes

5.2.1 Width of the Tropics and Global Circulation

Evidence continues to mount for an expansion of the tropics over the past several decades, with a poleward expansion of the Hadley cell and an associated poleward shift of the subtropical dry zones and storm tracks in each hemisphere.[5, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] The rate of expansion is uncertain and depends on the metrics and data sources that are used. Recent estimates of the widening of the global tropics for the period 1979–2009 range between 1° and 3° latitude (between about 70 and 200 miles) in each hemisphere, an average trend of between approximately 0.5° and 1.0° per decade.[26] While the roles of increasing greenhouse gases in both hemispheres,[4, 30] stratospheric ozone depletion in the Southern Hemisphere,[31] and anthropogenic aerosols in the Northern Hemisphere[32, 33] have been implicated as contributors to the observed expansion, there is uncertainty in the relative contributions of natural and anthropogenic factors, and natural variability may currently be dominating.[23, 34, 35]

Most of the previous work on tropical expansion to date has focused on zonally averaged changes. There are only a few recent studies that diagnose regional characteristics of tropical expansion. The findings depend on analysis methods and datasets. For example, a northward expansion of the tropics in most regions of the Northern Hemisphere, including the Eastern Pacific with impact on drying in the American Southwest, is found based on diagnosing outgoing longwave radiation.[36] However, other studies do not find a significant poleward expansion of the tropics over the Eastern Pacific and North America.[37, 38] Thus, while some studies associate the observed drying of the U.S. Southwest with the poleward expansion of the tropics,[5, 39] regional impacts of the observed zonally averaged changes in the width of the tropics are not understood.

Due to human-induced greenhouse gas increases, the Hadley cell is *likely* to widen in the future, with an accompanying poleward shift in the subtropical dry zones, midlatitude jets, and storm tracks.[2, 4, 5, 40, 41, 42, 43] Large uncertainties remain in projected changes in non-zonal to regional circulation components and related changes in precipitation patterns.[18, 40, 44, 45] Uncertainties in projected changes in midlatitude jets are also related to the projected rate of arctic amplification and variations in the stratospheric polar vortex. Both factors could shift the midlatitude jet equatorward, especially in the North Atlantic region.[46, 47, 48, 49]

5.2.2 El Niño–Southern Oscillation

El Niño–Southern Oscillation (ENSO) is a main source of climate variability, with a two- to seven-year timescale, originating from coupled ocean–atmosphere interactions in the tropical Pacific. Major ENSO events affect weather patterns over many parts of the globe through atmospheric teleconnections. ENSO strongly affects precipitation and temperature in the United States with impacts being most pronounced during the cold season (Figure 5.2).[11, 50, 51, 52, 53] A cooling trend of the tropical Pacific Ocean that resembles La Niña conditions contributed to drying in southwestern North America from 1979 to 2006[54] and is found to explain most of the decrease in heavy daily precipitation events in the southern United States from 1979 to 2013.[55]

El Niño teleconnections are modulated by the location of maximum anomalous tropical Pacific sea surface temperatures (SST). Eastern Pacific (EP) El Niño events affect winter temperatures primarily over the Great Lakes, Northeast, and Southwest, while Central Pacific (CP) events influence temperatures primarily over the northwestern and southeastern United States.[56] The CP El Niño also enhances the drying effect, but weakens the wetting effect, typically produced by traditional EP El Niño events on U.S. winter precipitation.[57] It is not clear whether observed decadal-scale modulations of ENSO properties, including an increase in ENSO amplitude[58] and an increase in frequency of CP El Niño events,[59, 60] are due to internal variability or anthropogenic forcing. Uncertainties in both the diagnosed distinct U.S. climate effects of EP and CP events and causes for the decadal scale changes result from the limited sample size of observed ENSO events in each category[61, 62] and the relatively short record of the comprehensive observations (since late 1970s) that would allow the investigation of ENSO-related coupled atmosphere–ocean feedbacks.[19] Furthermore, unforced global climate model simulations show that decadal to centennial modulations of ENSO can be generated without any change in external forcing.[63] A model study based on large, single-model ensembles of atmospheric and coupled atmosphere–ocean models finds that external radiative forcing resulted in an atmospheric teleconnection pattern that is independent of ENSO-like variations during the 1979–2014 period and is characterized by a hemisphere-scale increasing trend in heights.[53]

The representation of ENSO in climate models has improved from CMIP3 to CMIP5 models, especially in relation to ENSO amplitude.[64, 65] However, CMIP5 models still cannot capture the seasonal timing of ENSO events.[66] Furthermore, they still exhibit errors in simulating key atmospheric feedbacks, and the improvement in ENSO amplitudes might therefore result from error compensations.[64] Limited observational records and the nonstationarity of tropical Pacific teleconnections to North America on multidecadal time scales pose challenges for evaluating teleconnections between ENSO and U.S. climate in coupled atmosphere–ocean models.[61, 67] For a given SST forcing, however, the atmospheric component of CMIP5 models simulate the sign of the precipitation change over the southern section of North America.[68]

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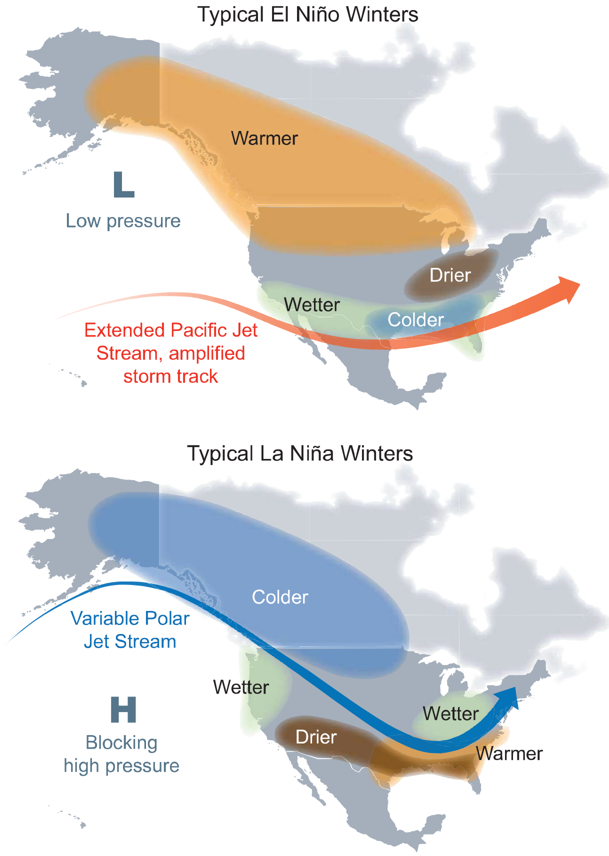

Figure 5.2: El Niño- and La Niña-related winter features over North America. Shown are typical January to March weather anomalies and atmospheric circulation during moderate to strong El Niño and La Niña conditions: (top) During El Niño, there is a tendency for a strong jet stream and storm track across the southern part of the United States. The southern tier of Alaska and the U.S. Pacific Northwest tend to be warmer than average, whereas the southern tier of United States tends to be cooler and wetter than average. (bottom) During La Niña, there is a tendency of a very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the North and warmer and less stormy conditions across the South. (Figure source: adapted from Lindsey 2016[178]).

Climate projections suggest that ENSO will remain a primary mode of natural climate variability in the 21st century.[19] Climate models do not agree, however, on projected changes in the intensity or spatial pattern of ENSO.[19] This uncertainty is related to a model dependence of simulated changes in the zonal gradient of tropical Pacific sea surface temperature in a warming climate.[19] Model studies suggest an eastward shift of ENSO-induced teleconnection patterns due to greenhouse gas-induced climate change.[69, 70, 71, 72] However, the impact of such a shift on ENSO-induced climate anomalies in the United States is not well understood.[72, 73]

In summary, there is *high confidence* that, in the 21st century, ENSO will remain a main source of climate variability over the United States on seasonal to interannual timescales. There is *low confidence* for a specific projected change in ENSO variability.

5.2.3 Extra-tropical Modes of Variability and Phenomena

North Atlantic Oscillation and Northern Annular Mode

The North Atlantic Oscillation (NAO), the leading recurring mode of variability in the extratropical North Atlantic region, describes an opposing pattern of sea level pressure

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between the Atlantic subtropical high and the Iceland/Arctic low. Variations in the NAO are accompanied by changes in the location and intensity of the Atlantic midlatitude storm track and blocking activity that affect climate over the North Atlantic and surrounding continents. A negative NAO phase is related to anomalously cold conditions and an enhanced number of cold outbreaks in the eastern United States, while a strong positive phase of the NAO tends to be associated with above-normal temperatures in this region.[7, 74] The positive phase of the NAO is associated with increased precipitation frequency and positive daily rainfall anomalies, including extreme daily precipitation anomalies in the northeastern United States.[75, 76]

The Northern Annular Mode/Arctic Oscillation (NAM/AO) is closely related to the NAO. It describes a similar out-of-phase pressure variation between mid- and high latitudes but on a hemispheric rather than regional scale.[77, 78] The time series of the NAO and NAM/AO are highly correlated, with persistent NAO and NAM/AO events being indistinguishable.[79, 80]

The wintertime NAO/NAM index exhibits pronounced variability on multidecadal time scales, with an increase from the 1960s to the 1990s, a shift to a more negative phase since the 1990s due to a series of winters like 2009–2010 and 2010–2011 (which had exceptionally low index values), and a return to more positive values after 2011.[30] Decadal scale temperature trends in the eastern United States, including occurrences of cold outbreaks during recent years, are linked to these changes in the NAO/NAM.[81, 82, 83, 84]

The NAO's influence on the ocean occurs through changes in heat content, gyre circulations, mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover.[7, 85] Climate model simulations show that multidecadal variations in the NAO induce multidecadal variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC) and poleward ocean heat transport in the Atlantic, extending to the Arctic, with potential impacts on recent arctic sea ice loss and Northern Hemisphere warming.[85] However, other model simulations suggest that the NAO and recent changes in Northern Hemisphere climate were affected by recent variations in the AMOC,[86] for which enhanced freshwater discharge from the Greenland Ice Sheet (GrIS) may have been a contributing cause.[87]

Climate models are widely analyzed for their ability to simulate the spatial patterns of the NAO/NAM and their relationship to temperature and precipitation anomalies over the United States.[9, 65, 88] Climate models reproduce the broad spatial and temporal features of the NAO, although there are large differences among the individual models in the location of the NAO centers of action and their average magnitude. These differences affect the agreement between observed and simulated climate anomalies related to the NAO.[9, 65] Climate models tend to have a NAM pattern that is more annular than observed,[65, 88] resulting in a strong bias in the Pacific center of the NAM. As a result, temperature anomalies over the northwestern United States associated with the NAM in most models are of opposite sign compared to observation.[88] Biases in the model representation of NAO/NAM features are linked to limited abilities of general circulation models to reproduce dynamical processes, including atmospheric blocking,[89] troposphere–stratosphere coupling,[90] and climatological stationary waves.[90, 91]

The CMIP5 models on average simulate a progressive shift of the NAO/NAM towards the positive phase due to human-induced climate change.[92] However, the spread between model

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simulations is larger than the projected multimodel increase,[19] and there are uncertainties related to future scenarios.[9] Furthermore, it is found that shifts between preferred periods of positive and negative NAO phase will continue to occur similar to those observed in the past.[19, 93] There is no consensus on the location of changes of NAO centers among the global climate models under future warming scenarios.[9] Uncertainties in future projections of the NAO/NAM in some seasons are linked to model spread in projected future arctic warming[46, 47] (Ch. 11: Arctic Changes) and to how models resolve stratospheric processes.[19, 94]

In summary, while it is *likely* that the NAO/NAM index will become slightly more positive (on average) due to increases in GHGs, there is *low confidence* in temperature and precipitation changes over the United States related to such variations in the NAO/NAM.

North Pacific Oscillation/West Pacific Oscillation

The North Pacific Oscillation (NPO) is a recurring mode of variability in the extratropical North Pacific region and is characterized by a north-south seesaw in sea level pressure. Effects of NPO on U.S. hydroclimate and marginal ice zone extent in the arctic seas have been reported.[8]

The NPO is linked to tropical sea surface temperature variability. Specifically, NPO contributes to the excitation of ENSO events via the "Seasonal Footprinting Mechanism".[95, 96] In turn, warm events in the central tropical Pacific Ocean are suggested to force an NPO-like circulation pattern.[97] There is *low confidence* in future projections of the NPO due to the small number of modeling studies as well as the finding that many climate models do not properly simulate the observed linkages between the NPO and tropical sea surface temperature variability.[19, 98]

Pacific/North American Pattern

The Pacific/North American (PNA) pattern is the leading recurring mode of internal atmospheric variability over the North Pacific and the North American continent, especially during the cold season. It describes a quadripole pattern of mid-tropospheric height anomalies, with anomalies of similar sign located over the subtropical northeastern Pacific and northwestern North America and of the opposite sign centered over the Gulf of Alaska and the southeastern United States. The PNA pattern is associated with strong fluctuations in the strength and location of the East Asian jet stream. The positive phase of the PNA pattern is associated with above average temperatures over the western and northwestern United States, and below average temperatures across the south-central and southeastern United States, including an enhanced occurrence of extreme cold temperatures.[9, 99, 100] Significant negative correlation between the PNA and winter precipitation over the Ohio River Valley has been documented.[9, 99, 101] The PNA is related to ENSO events[102] and also serves as a bridge linking ENSO and NAO variability.[103]

Climate models are able to reasonably represent the atmospheric circulation and climate anomalies associated with the PNA pattern. However, individual models exhibit differences compared to the observed relationship, due to displacements of the simulated PNA centers of action and offsets in their magnitudes.[9] Climate models do not show consistent location changes of the PNA centers due to increases in GHGs.[9, 72] Therefore, there is *low confidence* for projected changes in the PNA and the association with temperature and precipitation variations over the United States.

Blocking and Quasi-Stationary Waves

Anomalous atmospheric flow patterns in the extratropics that remain in place for an ex-

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tended period of time (for example, blocking and quasi-stationary Rossby waves)—and thus affect a region with similar weather conditions like rain or clear sky for several days to weeks—can lead to flooding, drought, heat waves, and cold waves.[10, 104, 105] Specifically, blocking describes large-scale, persistent high pressure systems that interrupt the typical westerly flow, while planetary waves (Rossby waves) describe large-scale meandering of the atmospheric jet stream.

A persistent pattern of high pressure in the circulation off the West Coast of the United States has been associated with the recent multiyear California drought[106, 107, 108] (Ch. 8: Droughts, Floods, and Wildfire). Blocking in the Alaskan region, which is enhanced during La Niña winters (Figure 5.2),[109] is associated with higher temperatures in western Alaska but shift to lower mean and extreme surface temperatures from the Yukon southward to the southern Plains.[110] The anomalously cold winters of 2009–2010 and 2010–2011 in the United States are linked to the blocked (or negative) phase of the NAO.[111] Stationary Rossby wave patterns may have contributed to the North American temperature extremes during summers like 2011.[112] It has been suggested that arctic amplification has already led to weakened westerly winds and hence more slowly moving and amplified wave patterns and enhanced occurrence of blocking[113, 114] (Ch. 11: Arctic Changes). While some studies suggest an observed increase in the metrics of these persistent circulation patterns,[113, 115] other studies suggest that observed changes are small compared to atmospheric internal variability.[116, 117, 118]

A decrease of blocking frequency with climate change is found in CMIP3, CMIP5, and higher-resolution models.[19, 119, 120] Climate models robustly project a change in Northern Hemisphere winter quasi-stationary wave fields that are linked to a wetting of the North American West Coast,[45, 121, 122] due to a strengthening of the zonal mean westerlies in the subtropical upper troposphere. However, CMIP5 models still underestimate observed blocking activity in the North Atlantic sector while they tend to overestimate activity in the North Pacific, although with a large intermodel spread.[19] Most climate models also exhibit biases in the representation of relevant stationary waves.[44]

In summary, there is *low confidence* in projected changes in atmospheric blocking and wintertime quasi-stationary waves. Therefore, our confidence is *low* on the association between observed and projected changes in weather and climate extremes over the United States and variations in these persistent atmospheric circulation patterns.

5.2.4 Modes of Variability on Decadal to Multidecadal Time Scales

Pacific Decadal Oscillation (PDO) / Interdecadal Pacific Oscillation (IPO)

The Pacific Decadal Oscillation (PDO) was first introduced by Mantua et al. 1997[123] as the leading empirical orthogonal function of North Pacific (20°–70°N) monthly averaged sea surface temperature anomalies.[14] Interdecadal Pacific Oscillation (IPO) refers to the same phenomenon and is based on Pacific-wide sea surface temperatures. PDO/IPO lacks a characteristic timescale and represents a combination of physical processes that span the tropics and extratropics, including both remote tropical forcing and local North Pacific atmosphere–ocean interactions.[14] Consequently, PDO-related variations in temperature and precipitation in the United States are very similar to (and indeed may be caused by) variations associated with ENSO and the strength of the Aleutian low (North Pacific Index, NPI), as shown in Figure 5.3. A PDO-related temperature variation in Alaska is also apparent.[124, 125]

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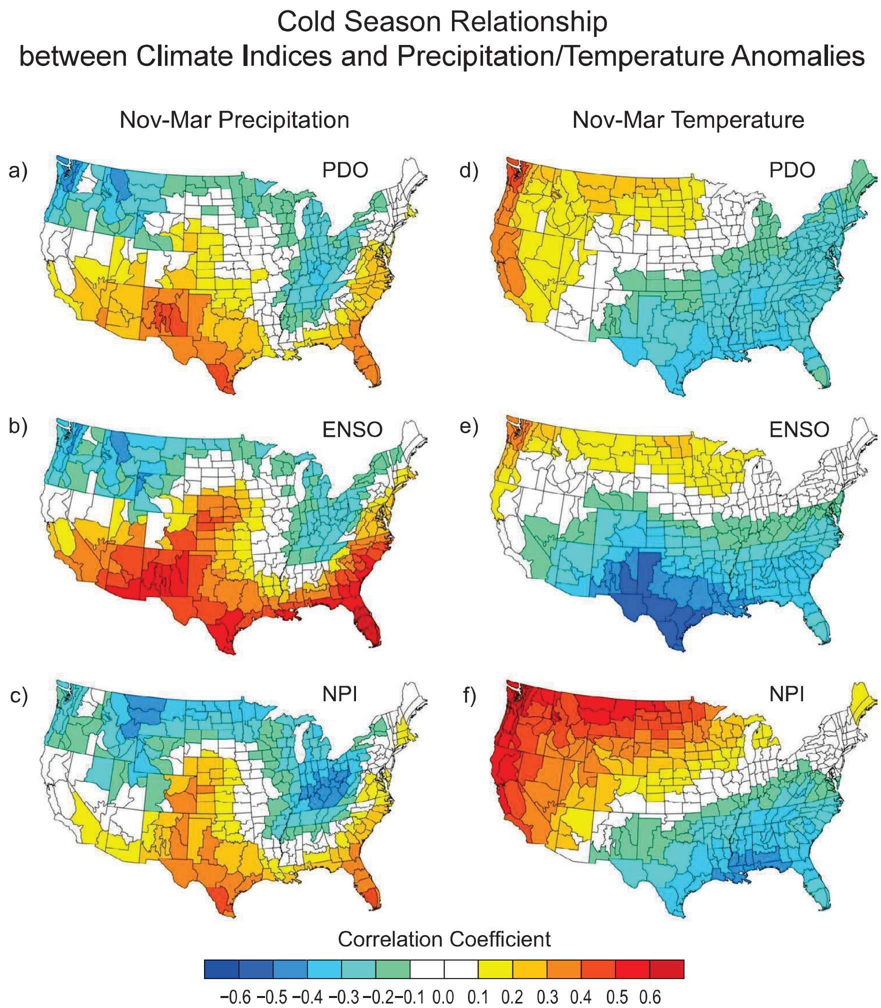

Figure 5.3: Cold season relationship between climate indices and U.S. precipitation and temperature anomalies determined from U.S. climate division data,[179] for the years 1901–2014. November–March mean U.S. precipitation anomalies correlated with (a) the Pacific Decadal Oscillation (PDO) index, (b) the El Niño–Southern Oscillation (ENSO) index, and (c) the North Pacific Index (NPI). November–March U.S. temperature anomalies correlated with (d) the PDO index, (e) the ENSO index, and (f) the NPI. United States temperature and precipitation related to the Pacific Decadal Oscillation are very similar to (and indeed may be caused by) variations associated with ENSO and the Aleutian low strength (North Pacific Index). (Figure source: Newman et al. 2016[14]; © American Meteorological Society, used with permission).

The PDO does not show a long-term trend either in SST reconstructions or in the ensemble mean of historical CMIP3 and CMIP5 simulations.[14] Emerging science suggests that externally forced natural and anthropogenic factors have contributed to the observed PDO-like variability. For example, a model study finds that the observed PDO phase is affected by large volcanic events and the variability in incoming solar radiation.[126] Aerosols from anthropogenic sources could change the temporal variability of the North Pacific SST through modifications of the atmospheric circulation.[127, 128] Furthermore, some studies show that periods with near-zero warming trends of global mean temperature and periods of accelerated temperatures could result from the interplay between internally generated PDO/IPO-like temperature variations in the tropical Pacific Ocean and greenhouse gas-induced ocean warming.[129, 130]

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Future changes in the spatial and temporal characteristics of PDO/IPO are uncertain. Based on CMIP3 models, one study finds that most of these models do not exhibit significant changes,[98] while another study points out that the PDO/IPO becomes weaker and more frequent by the end of the 21st century in some models.[131] Furthermore, future changes in ENSO variability, which strongly contributes to the PDO/IPO,[132] are also uncertain (Section 5.2.2). Therefore, there is *low confidence* in projected future changes in the PDO/IPO.

Atlantic Multidecadal Variability (AMV) / Atlantic Multidecadal Oscillation (AMO)

The North Atlantic Ocean region exhibits coherent multidecadal variability that exerts measurable impacts on regional climate for variables such as U.S. precipitation[12, 133, 134, 135] and Atlantic hurricane activity.[13, 136, 137, 138, 139, 140] This observed Atlantic multidecadal variability, or AMV, is generally understood to be driven by a combination of internal and external factors.[12, 141, 142, 143, 144, 145, 146, 147, 148] The AMV manifests in SST variability and patterns as well as synoptic-scale variability of atmospheric conditions. The internal part of the observed AMV is often referred to as the Atlantic Multidecadal Oscillation (AMO) and is putatively driven by changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC).[142, 143, 149, 150] It is important to understand the distinction between the AMO, which is often assumed to be natural (because of its putative relationship with natural AMOC variability), and AMV, which simply represents the observed multidecadal variability as a whole.

The relationship between observed AMV and the AMOC has recently been called into question and arguments have been made that AMV can occur in the absence of the AMOC via stochastic forcing of the ocean by coherent atmospheric circulation variability, but this is presently a topic of debate.[151, 152, 153, 154] Despite the ongoing debates, it is generally acknowledged that observed AMV, as a whole, represents a complex conflation of natural internal variability of the AMOC, natural red-noise stochastic forcing of the ocean by the atmosphere,[146] natural external variability from volcanic events[155, 156] and mineral aerosols,[157] and anthropogenic forcing from greenhouse gases and pollution aerosols.[158, 159, 160, 161]

As also discussed in Chapter 9: Extreme Storms (in the context of Atlantic hurricanes), determining the relative contributions of each mechanism to the observed multidecadal variability in the Atlantic is presently an active area of research and debate, and no consensus has yet been reached.[146, 161, 162, 163, 164, 165, 166] Still, despite the level of disagreement about the relative magnitude of human influences (particularly whether natural or anthropogenic factors are dominating), there is broad agreement in the literature of the past decade or so that human factors have had a measurable impact on the observed AMV. Furthermore, the AMO, as measured by indices constructed from environmental data (e.g., Enfield et al. 2001[12]), is generally based on detrended SST data and is then, by construction, segregated from the century-scale linear SST trends that are likely forced by increasing greenhouse gas concentrations. In particular, removal of a linear trend is not expected to account for all of the variability forced by changes in sulfate aerosol concentrations that have occurred over the past century. In this case, increasing sulfate aerosols are argued to cause cooling of Atlantic SST, thus offsetting the warming caused by increasing greenhouse gas concentration. After the Clean Air Act and Amendments of the 1970s, however, a steady reduction of sulfate aerosols is argued to have caused SST warming that compounds the warming from the ongoing increases in greenhouse gas concentrations.[160, 161] This combination of greenhouse

gas and sulfate aerosol forcing, by itself, can lead to Atlantic multidecadal SST variability that would not be removed by removing a linear trend.[155]

In summary, it is unclear what the statistically derived AMO indices represent, and it is not readily supportable to treat AMO index variability as tacitly representing natural variability, nor is it clear that the observed AMV is truly oscillatory in nature.[167] There is a physical basis for treating the AMOC as oscillatory (via thermohaline circulation arguments),[168] but there is no expectation of true oscillatory behavior in the hypothesized external forcing agents for the remaining variability. Detrending the SST data used to construct the AMO indices may partially remove the century-scale trends forced by increasing greenhouse gas concentrations, but it is not adequate for removing multidecadal variability forced by aerosol concentration variability. There is evidence that natural AMOC variability has been occurring for hundreds of years,[149, 169, 170, 171, 172] and this has apparently played some role in the observed AMV as a whole, but a growing body of evidence shows that external factors, both natural and anthropogenic, have played a substantial additional role in the past century.

5.3 Quantifying the Role of Internal Variability on Past and Future U.S. Climate Trends

The role of internal variability in masking trends is substantially increased on regional and local scales relative to the global scale, and in the extratropics relative to the tropics (Ch. 4: Projections). Approaches have been developed to better quantify the externally forced and internally driven contributions to observed and future climate trends and variability and further separate these contributions into thermodynamically and dynamically driven factors.[17] Specifically, large “initial condition” climate model ensembles with 30 ensemble members and more[93, 173, 174] and long control runs[175] have been shown to be useful tools to characterize uncertainties in climate change projections at local / regional scales.

North American temperature and precipitation trends on timescales of up to a few decades are strongly affected by intrinsic atmospheric circulation variability.[17, 173] For example, it is estimated that internal circulation trends account for approximately one-third of the observed wintertime warming over North America during the past 50 years. In a few areas, such as the central Rocky Mountains and far western Alaska, internal dynamics have offset the warming trend by 10%–30%.[17] Natural climate variability superimposed upon forced climate change will result in a large range of possible trends for surface air temperature and precipitation in the United States over the next 50 years (Figure 5.4).[173]

Climate models are evaluated with respect to their proper simulation of internal decadal variability. Comparing observed and simulated variability estimates at timescales longer than 10 years suggest that models tend to overestimate the internal variability in the northern extratropics, including over the continental United States, but underestimate it over much of the tropics and subtropical ocean regions.[93, 176] Such biases affect signal-to-noise estimates of regional scale climate change response and thus assessment of internally driven contributions to regional / local trends.

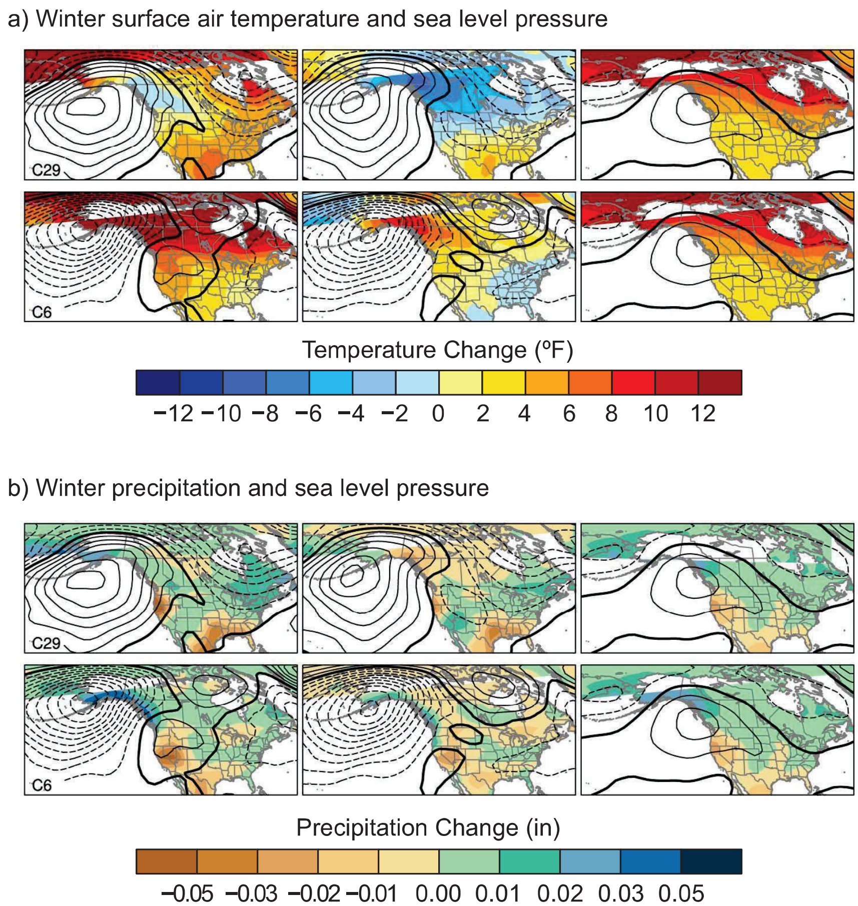

Figure 5.4: (left) Total 2010–2060 winter trends decomposed into (center) internal and (right) forced components for two contrasting CCSM3 ensemble members (runs 29 and 6) for (a) surface air temperature [color shading; °F/(51 years)] and sea level pressure (SLP; contours) and (b) precipitation [color shading; inches per day/(51 years)] and SLP (contours). SLP contour interval is 1 hPa/(51 years), with solid (dashed) contours for positive (negative) values; the zero contour is thickened. The same climate model (CCSM3) simulates a large range of possible trends in North American climate over the 2010–2060 period because of the influence of internal climate variability superposed upon forced climate trends. (Figure source: adapted from Deser et al. 2014;[173] © American Meteorological Society, used with permission).

TRACEABLE ACCOUNTS

Key Finding 1

The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities have played a role in this change (*medium confidence*), although confidence is presently *low* regarding the magnitude of the human contribution relative to natural variability

Description of evidence base

The Key Finding is supported by statements of the Intergovernmental Panel on Climate Change's Fifth Assessment Report[24] and a large number of more recent studies that examined the magnitude of the observed tropical widening and various causes.[5, 20, 22, 23, 25, 26, 27, 28, 29, 31] Additional evidence for an impact of greenhouse gas increases on the widening of the tropical belt and poleward shifts of the midlatitude jets is provided by the diagnosis of CMIP5 simulations.[4, 40] There is emerging evidence for an impact of anthropogenic aerosols on the tropical expansion in the Northern Hemisphere.[32, 33] Recent studies provide new evidence on the significance of internal variability on recent changes in the tropical width.[23, 34, 35]

Major uncertainties

The rate of observed expansion of tropics depends on which metric is used. The linkages between different metrics are not fully explored. Uncertainties also result from the utilization of reanalysis to determine trends and from limited observational records of free atmosphere circulation, precipitation, and evaporation. The dynamical mechanisms behind changes in the width of the tropical belt (e.g., tropical–extratropical interactions and baroclinic eddies) are not fully understood. There is also a limited understanding of how various climate forcings, such as anthropogenic aerosols, affect the width of tropics. The coarse horizontal and vertical resolution of global climate models may limit the ability of these models to properly resolve latitudinal changes in the atmospheric circulation. Limited observational records affect the ability to accurately estimate the contribution of natural decadal to multi-decadal variability on observed expansion of the tropics.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Medium to high confidence that the tropics and related features of the global circulation have expanded poleward is based upon the results of a large number of observational studies, using a wide variety of metrics and data sets, which reach similar conclusions. A large number of studies utilizing modeling of different complexity and theoretical considerations provide compounding evidence that human activities, including increases in greenhouse gases, ozone depletion, and anthropogenic aerosols, contributed to the observed poleward expansion of the tropics. Climate models forced with these anthropogenic drivers cannot explain the observed magnitude of tropical expansion and some studies suggest a possibly large contribution of internal variability. These multiple lines of evidence lead to the conclusion of *medium confidence* that human activities contributed to observed expansion of the tropics.

Summary sentence or paragraph that integrates the above information

The tropics have expanded poleward in each hemisphere over the period 1979–2009 (*medium* to *high confidence*) as shown by a large number of studies using a variety of metrics, observations and reanalysis. Modeling studies and theoretical considerations illustrate that human activities, including increases in greenhouse gases, ozone depletion, and anthropogenic aerosols, cause a widening of the tropics. There is *medium confidence* that human activities have contributed to the observed poleward expansion, taking into account uncertainties in the magnitude of observed trends and a possible large contribution of natural climate variability.

Key Finding 2

Recurring patterns of variability in large-scale atmospheric circulation (such as the North Atlantic Oscilla-

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tion and Northern Annular Mode) and the atmosphere–ocean system (such as El Niño–Southern Oscillation) cause year-to-year variations in U.S. temperatures and precipitation (*high confidence*). Changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends (*medium confidence*), although confidence is *low* regarding the size of the role of human activities in these changes.

Description of evidence base

The Key Finding is supported by a large number of studies that diagnose recurring patterns of variability and their changes, as well as their impact on climate over the United States. Regarding year-to-year variations, a large number of studies based on models and observations show statistically significant associations between North Atlantic Oscillation/Northern Annular Mode and United States temperature and precipitation,[7, 9, 74, 75, 76, 88] as well as El Niño–Southern Oscillation and related U.S. climate teleconnections.[11, 50, 51, 52, 53, 56, 57] Regarding recent decadal trends, several studies provide evidence for concurrent changes in the North Atlantic Oscillation/Northern Annular Mode and climate anomalies over the United States.[81, 82, 83, 84] Modeling studies provide evidence for a linkage between cooling trends of the tropical Pacific Ocean that resemble La Niña and precipitation changes in the southern United States.[54, 55] Several studies describe a decadal modification of ENSO.[58, 59, 60, 63] Modeling evidence is provided that such decadal modifications can be due to internal variability.[63] Climate models are widely analyzed for their ability to simulate recurring patterns of variability and teleconnections over the United States.[9, 64, 65, 68, 88, 98] Climate model projections are also widely analyzed to diagnose the impact of human activities on NAM/NAO, ENSO teleconnections, and other recurring modes of variability associated with climate anomalies.[9, 19, 72, 92]

Major uncertainties

A key uncertainty is related to limited observational records and our capability to properly simulate climate variability on decadal to multidecadal timescales, as well as to properly simulate recurring patterns of climate variability, underlying physical mechanisms, and associated variations in temperature and precipitation over the United States.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high confidence* that preferred patterns of variability affect U.S. temperature on a year-to-year timescale, based on a large number of studies that diagnose observational data records and long simulations. There is *medium confidence* that changes in the occurrence of these patterns or their properties have contributed to recent U.S. temperature and precipitation trends. Several studies agree on a linkage between decadal changes in the NAO/NAM and climate trends over the United States, and there is some modeling evidence for a linkage between a La Niña-like cooling trend over the tropical Pacific and precipitation changes in the southwestern United States. There is no robust evidence for observed decadal changes in the properties of ENSO and related United States climate impacts. Confidence is *low* regarding the size of the role of human influences in these changes because models do not agree on the impact of human activity on preferred patterns of variability or because projected changes are small compared to internal variability.

Summary sentence or paragraph that integrates the above information

Recurring modes of variability strongly affect temperature and precipitation over the United States on interannual timescales (*high confidence*) as supported by a very large number of observational and modeling studies. Changes in some recurring patterns of variability have contributed to recent trends in U.S. temperature and precipitation (*medium confidence*). The causes of these changes are uncertain due to the limited observational record and because models exhibit some difficulties simulating these recurring patterns of variability and their underlying physical mechanisms.

References

1. Frierson, D.M.W., J. Lu, and G. Chen, 2007: Width of the Hadley cell in simple and comprehensive general circulation models. *Geophysical Research Letters*, **34**, L18804. http://dx.doi.org/10.1029/2007GL031115

2. Mbengue, C. and T. Schneider, 2017: Storm-track shifts under climate change: Toward a mechanistic understanding using baroclinic mean available potential energy. *Journal of the Atmospheric Sciences*, **74**, 93-110. http://dx.doi.org/10.1175/jas-d-15-0267.1

3. Sun, Y., G. Ramstein, C. Contoux, and T. Zhou, 2013: A comparative study of large-scale atmospheric circulation in the context of a future scenario (RCP4.5) and past warmth (mid-Pliocene). *Climate of the Past*, **9**, 1613-1627. http://dx.doi.org/10.5194/cp-9-1613-2013

4. Vallis, G.K., P. Zurita-Gotor, C. Cairns, and J. Kidston, 2015: Response of the large-scale structure of the atmosphere to global warming. *Quarterly Journal of the Royal Meteorological Society*, **141**, 1479-1501. http://dx.doi.org/10.1002/qj.2456

5. Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmospheric Chemistry and Physics*, **13**, 10081-10094. http://dx.doi.org/10.5194/acp-13-10081-2013

6. Seidel, D.J., Q. Fu, W.J. Randel, and T.J. Reichler, 2008: Widening of the tropical belt in a changing climate. *Nature Geoscience*, **1**, 21-24. http://dx.doi.org/10.1038/ngeo.2007.38

7. Hurrell, J.W. and C. Deser, 2009: North Atlantic climate variability: The role of the North Atlantic oscillation. *Journal of Marine Systems*, **78**, 28-41. http://dx.doi.org/10.1016/j.jmarsys.2008.11.026

8. Linkin, M.E. and S. Nigam, 2008: The North Pacific Oscillation–West Pacific teleconnection pattern: Mature-phase structure and winter impacts. *Journal of Climate*, **21**, 1979-1997. http://dx.doi.org/10.1175/2007JCLI2048.1

9. Ning, L. and R.S. Bradley, 2016: NAO and PNA influences on winter temperature and precipitation over the eastern United States in CMIP5 GCMs. *Climate Dynamics*, **46**, 1257-1276. http://dx.doi.org/10.1007/s00382-015-2643-9

10. Grotjahn, R., R. Black, R. Leung, M.F. Wehner, M. Barlow, M. Bosilovich, A. Gershunov, W.J. Gutowski, J.R. Gyakum, R.W. Katz, Y.-Y. Lee, Y.-K. Lim, and Prabhat, 2016: North American extreme temperature events and related large scale meteorological patterns: A review of statistical methods, dynamics, modeling, and trends. *Climate Dynamics*, **46**, 1151-1184. http://dx.doi.org/10.1007/s00382-015-2638-6

11. Halpert, M.S. and C.F. Ropelewski, 1992: Surface temperature patterns associated with the Southern Oscillation. *Journal of Climate*, **5**, 577-593. http://dx.doi.org/10.1175/1520-0442(1992)005<0577:STPAWT>2.0.CO;2

12. Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble, 2001: The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters*, **28**, 2077-2080. http://dx.doi.org/10.1029/2000GL012745

13. Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nuñez, and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, **293**, 474-479. http://dx.doi.org/10.1126/science.1060040

14. Newman, M., M.A. Alexander, T.R. Ault, K.M. Cobb, C. Deser, E.D. Lorenzo, N.J. Mantua, A.J. Miller, S. Minobe, H. Nakamura, N. Schneider, D.J. Vimont, A.S. Phillips, J.D. Scott, and C.A. Smith, 2016: The Pacific Decadal Oscillation, revisited. *Journal of Climate*, **29**, 4399-4427. http://dx.doi.org/10.1175/JCLI-D-15-0508.1

15. Perlwitz, J., S. Pawson, R.L. Fogt, J.E. Nielsen, and W.D. Neff, 2008: Impact of stratospheric ozone hole recovery on Antarctic climate. *Geophysical Research Letters*, **35**, L08714. http://dx.doi.org/10.1029/2008GL033317

16. Palmer, T.N., F.J. Doblas-Reyes, A. Weisheimer, and M.J. Rodwell, 2008: Toward seamless prediction: Calibration of climate change projections using seasonal forecasts. *Bulletin of the American Meteorological Society*, **89**, 459-470. http://dx.doi.org/10.1175/bams-89-4-459

17. Deser, C., L. Terray, and A.S. Phillips, 2016: Forced and internal components of winter air temperature trends over North America during the past 50 years: Mechanisms and implications. *Journal of Climate*, **29**, 2237-2258. http://dx.doi.org/10.1175/JCLI-D-15-0304.1

18. Shepherd, T.G., 2014: Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience*, **7**, 703-708. http://dx.doi.org/10.1038/ngeo2253

FHWA001646

19. Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1217–1308. http://www.climatechange2013.org/report/full-report/

20. Birner, T., S.M. Davis, and D.J. Seidel, 2014: The changing width of Earth's tropical belt. *Physcis Today*, **67**, 38-44. http://dx.doi.org/10.1063/PT.3.2620

21. Brönnimann, S., A.M. Fischer, E. Rozanov, P. Poli, G.P. Compo, and P.D. Sardeshmukh, 2015: Southward shift of the northern tropical belt from 1945 to 1980. *Nature Geoscience*, **8**, 969-974. http://dx.doi.org/10.1038/ngeo2568

22. Davis, N.A. and T. Birner, 2013: Seasonal to multidecadal variability of the width of the tropical belt. *Journal of Geophysical Research Atmospheres*, **118**, 7773-7787. http://dx.doi.org/10.1002/jgrd.50610

23. Garfinkel, C.I., D.W. Waugh, and L.M. Polvani, 2015: Recent Hadley cell expansion: The role of internal atmospheric variability in reconciling modeled and observed trends. *Geophysical Research Letters*, **42**, 10,824-10,831. http://dx.doi.org/10.1002/2015GL066942

24. Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254. http://www.climatechange2013.org/report/full-report/

25. Karnauskas, K.B. and C.C. Ummenhofer, 2014: On the dynamics of the Hadley circulation and subtropical drying. *Climate Dynamics*, **42**, 2259-2269. http://dx.doi.org/10.1007/s00382-014-2129-1

26. Lucas, C., B. Timbal, and H. Nguyen, 2014: The expanding tropics: A critical assessment of the observational and modeling studies. *Wiley Interdisciplinary Reviews: Climate Change*, **5**, 89-112. http://dx.doi.org/10.1002/wcc.251

27. Norris, J.R., R.J. Allen, A.T. Evan, M.D. Zelinka, C.W. O'Dell, and S.A. Klein, 2016: Evidence for climate change in the satellite cloud record. *Nature*, **536**, 72-75. http://dx.doi.org/10.1038/nature18273

28. Quan, X.-W., M.P. Hoerling, J. Perlwitz, H.F. Diaz, and T. Xu, 2014: How fast are the tropics expanding? *Journal of Climate*, **27**, 1999-2013. http://dx.doi.org/10.1175/JCLI-D-13-00287.1

29. Reichler, T., 2016: Chapter 6 - Poleward expansion of the atmospheric circulation *Climate Change (Second Edition)*. Letcher, T.M., Ed. Elsevier, Boston, 79-104. http://dx.doi.org/10.1016/B978-0-444-63524-2.00006-3

30. Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

31. Waugh, D.W., C.I. Garfinkel, and L.M. Polvani, 2015: Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? *Journal of Climate*, **28**, 6581-6586. http://dx.doi.org/10.1175/JCLI-D-15-0138.1

32. Allen, R.J., S.C. Sherwood, J.R. Norris, and C.S. Zender, 2012: Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature*, **485**, 350-354. http://dx.doi.org/10.1038/nature11097

33. Kovilakam, M. and S. Mahajan, 2015: Black carbon aerosol-induced Northern Hemisphere tropical expansion. *Geophysical Research Letters*, **42**, 4964-4972. http://dx.doi.org/10.1002/2015GL064559

34. Adam, O., T. Schneider, and N. Harnik, 2014: Role of changes in mean temperatures versus temperature gradients in the recent widening of the Hadley circulation. *Journal of Climate*, **27**, 7450-7461. http://dx.doi.org/10.1175/JCLI-D-14-00140.1

35. Allen, R.J., J.R. Norris, and M. Kovilakam, 2014: Influence of anthropogenic aerosols and the Pacific Decadal Oscillation on tropical belt width. *Nature Geoscience*, **7**, 270-274. http://dx.doi.org/10.1038/ngeo2091

36. Chen, S., K. Wei, W. Chen, and L. Song, 2014: Regional changes in the annual mean Hadley circulation in recent decades. *Journal of Geophysical Research Atmospheres*, **119**, 7815-7832. http://dx.doi.org/10.1002/2014JD021540

37. Lucas, C. and H. Nguyen, 2015: Regional characteristics of tropical expansion and the role of climate variability. *Journal of Geophysical Research Atmospheres*, **120**, 6809-6824. http://dx.doi.org/10.1002/2015JD023130

38. Schwendike, J., G.J. Berry, M.J. Reeder, C. Jakob, P. Govekar, and R. Wardle, 2015: Trends in the local Hadley and local Walker circulations. *Journal of Geophysical Research Atmospheres*, **120**, 7599-7618. http://dx.doi.org/10.1002/2014JD022652

39. Prein, A.F., G.J. Holland, R.M. Rasmussen, M.P. Clark, and M.R. Tye, 2016: Running dry: The U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43**, 1272-1279. http://dx.doi.org/10.1002/2015GL066727

40. Barnes, E.A. and L. Polvani, 2013: Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. *Journal of Climate*, **26**, 7117-7135. http://dx.doi.org/10.1175/JCLI-D-12-00536.1

41. Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

42. Scheff, J. and D. Frierson, 2012: Twenty-first-century multimodel subtropical precipitation declines are mostly midlatitude shifts. *Journal of Climate*, **25**, 4330-4347. http://dx.doi.org/10.1175/JCLI-D-11-00393.1

43. Scheff, J. and D.M.W. Frierson, 2012: Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones. *Geophysical Research Letters*, **39**, L18704. http://dx.doi.org/10.1029/2012GL052910

44. Simpson, I.R., R. Seager, M. Ting, and T.A. Shaw, 2016: Causes of change in Northern Hemisphere winter meridional winds and regional hydroclimate. *Nature Climate Change*, **6**, 65-70. http://dx.doi.org/10.1038/nclimate2783

45. Simpson, I.R., T.A. Shaw, and R. Seager, 2014: A diagnosis of the seasonally and longitudinally varying midlatitude circulation response to global warming. *Journal of the Atmospheric Sciences*, **71**, 2489-2515. http://dx.doi.org/10.1175/JAS-D-13-0325.1

46. Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of Arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28**, 5254-5271. http://dx.doi.org/10.1175/JCLI-D-14-00589.1

47. Cattiaux, J. and C. Cassou, 2013: Opposite CMIP3/CMIP5 trends in the wintertime Northern Annular Mode explained by combined local sea ice and remote tropical influences. *Geophysical Research Letters*, **40**, 3682-3687. http://dx.doi.org/10.1002/grl.50643

48. Karpechko, A.Y. and E. Manzini, 2012: Stratospheric influence on tropospheric climate change in the Northern Hemisphere. *Journal of Geophysical Research*, **117**, D05133. http://dx.doi.org/10.1029/2011JD017036

49. Scaife, A.A., T. Spangehl, D.R. Fereday, U. Cubasch, U. Langematz, H. Akiyoshi, S. Bekki, P. Braesicke, N. Butchart, M.P. Chipperfield, A. Gettelman, S.C. Hardiman, M. Michou, E. Rozanov, and T.G. Shepherd, 2012: Climate change projections and stratosphere–troposphere interaction. *Climate Dynamics*, **38**, 2089-2097. http://dx.doi.org/10.1007/s00382-011-1080-7

50. Hoerling, M.P., A. Kumar, and T. Xu, 2001: Robustness of the nonlinear climate response to ENSO's extreme phases. *Journal of Climate*, **14**, 1277-1293. http://dx.doi.org/10.1175/1520-0442(2001)014<1277:ROTNCR>2.0.CO;2

51. Kiladis, G.N. and H.F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate*, **2**, 1069-1090. http://dx.doi.org/10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2

52. Ropelewski, C.F. and M.S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, **115**, 1606-1626. http://dx.doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2

FHWA001648

53. Zhang, T., M.P. Hoerling, J. Perlwitz, and T. Xu, 2016: Forced atmospheric teleconnections during 1979–2014. *Journal of Climate*, **29**, 2333-2357. http://dx.doi.org/10.1175/jcli-d-15-0226.1

54. Hoerling, M., J. Eischeid, and J. Perlwitz, 2010: Regional precipitation trends: Distinguishing natural variability from anthropogenic forcing. *Journal of Climate*, **23**, 2131-2145. http://dx.doi.org/10.1175/2009jcli3420.1

55. Hoerling, M., J. Eischeid, J. Perlwitz, X.-W. Quan, K. Wolter, and L. Cheng, 2016: Characterizing recent trends in U.S. heavy precipitation. *Journal of Climate*, **29**, 2313-2332. http://dx.doi.org/10.1175/jcli-d-15-0441.1

56. Yu, J.-Y., Y. Zou, S.T. Kim, and T. Lee, 2012: The changing impact of El Niño on US winter temperatures. *Geophysical Research Letters*, **39**, L15702. http://dx.doi.org/10.1029/2012GL052483

57. Yu, J.-Y. and Y. Zou, 2013: The enhanced drying effect of Central-Pacific El Niño on US winter. *Environmental Research Letters*, **8**, 014019. http://dx.doi.org/10.1088/1748-9326/8/1/014019

58. Li, J., S.-P. Xie, E.R. Cook, G. Huang, R. D'Arrigo, F. Liu, J. Ma, and X.-T. Zheng, 2011: Interdecadal modulation of El Niño amplitude during the past millennium. *Nature Climate Change*, **1**, 114-118. http://dx.doi.org/10.1038/nclimate1086

59. Lee, T. and M.J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters*, **37**, L14603. http://dx.doi.org/10.1029/2010GL044007

60. Yeh, S.-W., J.-S. Kug, B. Dewitte, M.-H. Kwon, B.P. Kirtman, and F.-F. Jin, 2009: El Niño in a changing climate. *Nature*, **461**, 511-514. http://dx.doi.org/10.1038/nature08316

61. Deser, C., I.R. Simpson, K.A. McKinnon, and A.S. Phillips, 2017: The Northern Hemisphere extratropical atmospheric circulation response to ENSO: How well do we know it and how do we evaluate models accordingly? *Journal of Climate*, **30**, 5059-5082. http://dx.doi.org/10.1175/jcli-d-16-0844.1

62. Garfinkel, C.I., M.M. Hurwitz, D.W. Waugh, and A.H. Butler, 2013: Are the teleconnections of Central Pacific and Eastern Pacific El Niño distinct in boreal wintertime? *Climate Dynamics*, **41**, 1835-1852. http://dx.doi.org/10.1007/s00382-012-1570-2

63. Capotondi, A., A.T. Wittenberg, M. Newman, E.D. Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider, Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bulletin of the American Meteorological Society*, **96 (12)**, 921-938. http://dx.doi.org/10.1175/BAMS-D-13-00117.1

64. Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation in climate models: From CMIP3 to CMIP5. *Climate Dynamics*, **42**, 1999-2018. http://dx.doi.org/10.1007/s00382-013-1783-z

65. Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–866. http://www.climatechange2013.org/report/full-report/

66. Sheffield, J., S.J. Camargo, R. Fu, Q. Hu, X. Jiang, N. Johnson, K.B. Karnauskas, S.T. Kim, J. Kinter, S. Kumar, B. Langenbrunner, E. Maloney, A. Mariotti, J.E. Meyerson, J.D. Neelin, S. Nigam, Z. Pan, A. Ruiz-Barradas, R. Seager, Y.L. Serra, D.-Z. Sun, C. Wang, S.-P. Xie, J.-Y. Yu, T. Zhang, and M. Zhao, 2013: North American climate in CMIP5 experiments. Part II: Evaluation of historical simulations of intraseasonal to decadal variability. *Journal of Climate*, **26**, 9247-9290. http://dx.doi.org/10.1175/jcli-d-12-00593.1

67. Coats, S., J.E. Smerdon, B.I. Cook, and R. Seager, 2013: Stationarity of the tropical pacific teleconnection to North America in CMIP5/PMIP3 model simulations. *Geophysical Research Letters*, **40**, 4927-4932. http://dx.doi.org/10.1002/grl.50938

68. Langenbrunner, B. and J.D. Neelin, 2013: Analyzing ENSO teleconnections in CMIP models as a measure of model fidelity in simulating precipitation. *Journal of Climate*, **26**, 4431-4446. http://dx.doi.org/10.1175/jcli-d-12-00542.1

69. Kug, J.-S., S.-I. An, Y.-G. Ham, and I.-S. Kang, 2010: Changes in El Niño and La Niña teleconnections over North Pacific–America in the global warming simulations. *Theoretical and Applied Climatology*, **100**, 275-282. http://dx.doi.org/10.1007/s00704-009-0183-0

FHWA001649

70. Meehl, G.A. and H. Teng, 2007: Multi-model changes in El Niño teleconnections over North America in a future warmer climate. *Climate Dynamics*, **29**, 779-790. http://dx.doi.org/10.1007/s00382-007-0268-3

71. Stevenson, S.L., 2012: Significant changes to ENSO strength and impacts in the twenty-first century: Results from CMIP5. *Geophysical Research Letters*, **39**, L17703. http://dx.doi.org/10.1029/2012GL052759

72. Zhou, Z.-Q., S.-P. Xie, X.-T. Zheng, Q. Liu, and H. Wang, 2014: Global warming–induced changes in El Niño teleconnections over the North Pacific and North America. *Journal of Climate*, **27**, 9050-9064. http://dx.doi.org/10.1175/JCLI-D-14-00254.1

73. Seager, R., N. Naik, and L. Vogel, 2012: Does global warming cause intensified interannual hydroclimate variability? *Journal of Climate*, **25**, 3355-3372. http://dx.doi.org/10.1175/JCLI-D-11-00363.1

74. Thompson, D.W.J. and J.M. Wallace, 2001: Regional climate impacts of the Northern Hemisphere annular mode. *Science*, **293**, 85-89. http://dx.doi.org/10.1126/science.1058958

75. Archambault, H.M., L.F. Bosart, D. Keyser, and A.R. Aiyyer, 2008: Influence of large-scale flow regimes on cool-season precipitation in the northeastern United States. *Monthly Weather Review*, **136**, 2945-2963. http://dx.doi.org/10.1175/2007MWR2308.1

76. Durkee, J.D., J.D. Frye, C.M. Fuhrmann, M.C. Lacke, H.G. Jeong, and T.L. Mote, 2008: Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the eastern United States. *Theoretical and Applied Climatology*, **94**, 51-65. http://dx.doi.org/10.1007/s00704-007-0345-x

77. Thompson, D.W.J. and J.M. Wallace, 1998: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, **25**, 1297-1300. http://dx.doi.org/10.1029/98GL00950

78. Thompson, D.W.J. and J.M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate*, **13**, 1000-1016. http://dx.doi.org/10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2

79. Deser, C., 2000: On the teleconnectivity of the "Arctic Oscillation". *Geophysical Research Letters*, **27**, 779-782. http://dx.doi.org/10.1029/1999GL010945

80. Feldstein, S.B. and C. Franzke, 2006: Are the North Atlantic Oscillation and the Northern Annular Mode distinguishable? *Journal of the Atmospheric Sciences*, **63**, 2915-2930. http://dx.doi.org/10.1175/JAS3798.1

81. Cohen, J. and M. Barlow, 2005: The NAO, the AO, and global warming: How closely related? *Journal of Climate*, **18**, 4498-4513. http://dx.doi.org/10.1175/jcli3530.1

82. Hurrell, J.W., 1995: Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. *Science*, **269**, 676-679. http://dx.doi.org/10.1126/science.269.5224.676

83. Overland, J., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma, 2015: The melting Arctic and midlatitude weather patterns: Are they connected? *Journal of Climate*, **28**, 7917-7932. http://dx.doi.org/10.1175/JCLI-D-14-00822.1

84. Overland, J.E. and M. Wang, 2015: Increased variability in the early winter subarctic North American atmospheric circulation. *Journal of Climate*, **28**, 7297-7305. http://dx.doi.org/10.1175/jcli-d-15-0395.1

85. Delworth, T.L., F. Zeng, G.A. Vecchi, X. Yang, L. Zhang, and R. Zhang, 2016: The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. *Nature Geoscience*, **9**, 509-512. http://dx.doi.org/10.1038/ngeo2738

86. Peings, Y. and G. Magnusdottir, 2014: Forcing of the wintertime atmospheric circulation by the multidecadal fluctuations of the North Atlantic ocean. *Environmental Research Letters*, **9**, 034018. http://dx.doi.org/10.1088/1748-9326/9/3/034018

87. Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016: Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications*, **7**, 10525. http://dx.doi.org/10.1038/ncomms10525

88. Gong, H., L. Wang, W. Chen, X. Chen, and D. Nath, 2017: Biases of the wintertime Arctic Oscillation in CMIP5 models. *Environmental Research Letters*, **12**, 014001. http://dx.doi.org/10.1088/1748-9326/12/1/014001

89. Davini, P. and C. Cagnazzo, 2014: On the misinterpretation of the North Atlantic Oscillation in CMIP5 models. *Climate Dynamics*, **43**, 1497-1511. http://dx.doi.org/10.1007/s00382-013-1970-y

90. Shaw, T.A., J. Perlwitz, and O. Weiner, 2014: Troposphere-stratosphere coupling: Links to North Atlantic weather and climate, including their representation in CMIP5 models. *Journal of Geophysical Research Atmospheres*, **119**, 5864-5880. http://dx.doi.org/10.1002/2013JD021191

91. Lee, Y.-Y. and R.X. Black, 2013: Boreal winter low-frequency variability in CMIP5 models. *Journal of Geophysical Research Atmospheres*, **118**, 6891-6904. http://dx.doi.org/10.1002/jgrd.50493

92. Gillett, N.P. and J.C. Fyfe, 2013: Annular mode changes in the CMIP5 simulations. *Geophysical Research Letters*, **40**, 1189-1193. http://dx.doi.org/10.1002/grl.50249

93. Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, **38**, 527-546. http://dx.doi.org/10.1007/s00382-010-0977-x

94. Manzini, E., A.Y. Karpechko, J. Anstey, M.P. Baldwin, R.X. Black, C. Cagnazzo, N. Calvo, A. Charlton-Perez, B. Christiansen, P. Davini, E. Gerber, M. Giorgetta, L. Gray, S.C. Hardiman, Y.Y. Lee, D.R. Marsh, B.A. McDaniel, A. Purich, A.A. Scaife, D. Shindell, S.W. Son, S. Watanabe, and G. Zappa, 2014: Northern winter climate change: Assessment of uncertainty in CMIP5 projections related to stratosphere-troposphere coupling. *Journal of Geophysical Research Atmospheres*, **119**, 7979-7998. http://dx.doi.org/10.1002/2013JD021403

95. Alexander, M.A., D.J. Vimont, P. Chang, and J.D. Scott, 2010: The impact of extratropical atmospheric variability on ENSO: Testing the seasonal footprinting mechanism using coupled model experiments. *Journal of Climate*, **23**, 2885-2901. http://dx.doi.org/10.1175/2010jcli3205.1

96. Vimont, D.J., J.M. Wallace, and D.S. Battisti, 2003: The seasonal footprinting mechanism in the Pacific: Implications for ENSO. *Journal of Climate*, **16**, 2668-2675. http://dx.doi.org/10.1175/1520-0442(2003)016<2668:tsfmit>2.0.co;2

97. Di Lorenzo, E., K.M. Cobb, J.C. Furtado, N. Schneider, B.T. Anderson, A. Bracco, M.A. Alexander, and D.J. Vimont, 2010: Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience*, **3**, 762-765. http://dx.doi.org/10.1038/ngeo984

98. Furtado, J.C., E.D. Lorenzo, N. Schneider, and N.A. Bond, 2011: North Pacific decadal variability and climate change in the IPCC AR4 models. *Journal of Climate*, **24**, 3049-3067. http://dx.doi.org/10.1175/2010JCLI3584.1

99. Leathers, D.J., B. Yarnal, and M.A. Palecki, 1991: The Pacific/North American teleconnection pattern and United States climate. Part I: Regional temperature and precipitation associations. *Journal of Climate*, **4**, 517-528. http://dx.doi.org/10.1175/1520-0442(1991)004<0517:TPATPA>2.0.CO;2

100. Loikith, P.C. and A.J. Broccoli, 2012: Characteristics of observed atmospheric circulation patterns associated with temperature extremes over North America. *Journal of Climate*, **25**, 7266-7281. http://dx.doi.org/10.1175/JCLI-D-11-00709.1

101. Coleman, J.S.M. and J.C. Rogers, 2003: Ohio River valley winter moisture conditions associated with the Pacific–North American teleconnection pattern. *Journal of Climate*, **16**, 969-981. http://dx.doi.org/10.1175/1520-0442(2003)016<0969:ORVWMC>2.0.CO;2

102. Nigam, S., 2003: Teleconnections. *Encyclopedia of Atmospheric Sciences*. Holton, J.R., Ed. Academic Press, 2243-2269.

103. Li, Y. and N.-C. Lau, 2012: Impact of ENSO on the atmospheric variability over the North Atlantic in late winter—Role of transient eddies. *Journal of Climate*, **25**, 320-342. http://dx.doi.org/10.1175/JCLI-D-11-00037.1

104. Petoukhov, V., S. Rahmstorf, S. Petri, and H.J. Schellnhuber, 2013: Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the National Academy of Sciences*, **110**, 5336-5341. http://dx.doi.org/10.1073/pnas.1222000110

105. Whan, K., F. Zwiers, and J. Sillmann, 2016: The influence of atmospheric blocking on extreme winter minimum temperatures in North America. *Journal of Climate*, **29**, 4361-4381. http://dx.doi.org/10.1175/JCLI-D-15-0493.1

106. Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28**, 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

107. Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh, 2014: The extraordinary California drought of 2013/14: Character, context and the role of climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **95 (9)**, S3-S6. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

108. Teng, H. and G. Branstator, 2017: Causes of extreme ridges that induce California droughts. *Journal of Climate*, **30**, 1477-1492. http://dx.doi.org/10.1175/jcli-d-16-0524.1

109. Renwick, J.A. and J.M. Wallace, 1996: Relationships between North Pacific wintertime blocking, El Niño, and the PNA pattern. *Monthly Weather Review*, **124**, 2071-2076. http://dx.doi.org/10.1175/1520-0493(1996)124<2071:RBNPWB>2.0.CO;2

FHWA001651

110. Carrera, M.L., R.W. Higgins, and V.E. Kousky, 2004: Downstream weather impacts associated with atmospheric blocking over the northeast Pacific. *Journal of Climate*, **17**, 4823-4839. http://dx.doi.org/10.1175/JCLI-3237.1

111. Guirguis, K., A. Gershunov, R. Schwartz, and S. Bennett, 2011: Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophysical Research Letters*, **38**, L17701. http://dx.doi.org/10.1029/2011GL048762

112. Wang, H., S. Schubert, R. Koster, Y.-G. Ham, and M. Suarez, 2014: On the role of SST forcing in the 2011 and 2012 extreme U.S. heat and drought: A study in contrasts. *Journal of Hydrometeorology*, **15**, 1255-1273. http://dx.doi.org/10.1175/JHM-D-13-069.1

113. Francis, J.A. and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, **39**, L06801. http://dx.doi.org/10.1029/2012GL051000

114. Francis, J.A., S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude weather: Emerging connections. *Wiley Interdesciplinary Review: Climate Change*, **8**, e474. http://dx.doi.org/10.1002/wcc.474

115. Hanna, E., T.E. Cropper, R.J. Hall, and J. Cappelen, 2016: Greenland blocking index 1851–2015: A regional climate change signal. *International Journal of Climatology*, **36**, 4847-4861. http://dx.doi.org/10.1002/joc.4673

116. Barnes, E.A., 2013: Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophysical Research Letters*, **40**, 4734-4739. http://dx.doi.org/10.1002/grl.50880

117. Barnes, E.A., E. Dunn-Sigouin, G. Masato, and T. Woollings, 2014: Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters*, **41**, 638-644. http://dx.doi.org/10.1002/2013GL058745

118. Screen, J.A. and I. Simmonds, 2013: Exploring links between Arctic amplification and mid-latitude weather. *Geophysical Research Letters*, **40**, 959-964. http://dx.doi.org/10.1002/grl.50174

119. Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes. *Current Climate Change Reports*, **1**, 115-124. http://dx.doi.org/10.1007/s40641-015-0020-8

120. Kennedy, D., T. Parker, T. Woollings, B. Harvey, and L. Shaffrey, 2016: The response of high-impact blocking weather systems to climate change. *Geophysical Research Letters*, **43**, 7250-7258. http://dx.doi.org/10.1002/2016GL069725

121. Brandefelt, J. and H. Körnich, 2008: Northern Hemisphere stationary waves in future climate projections. *Journal of Climate*, **21**, 6341-6353. http://dx.doi.org/10.1175/2008JCLI2373.1

122. Haarsma, R.J. and F. Selten, 2012: Anthropogenic changes in the Walker circulation and their impact on the extra-tropical planetary wave structure in the Northern Hemisphere. *Climate Dynamics*, **39**, 1781-1799. http://dx.doi.org/10.1007/s00382-012-1308-1

123. Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, **78**, 1069-1080. http://dx.doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

124. Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate*, **18**, 4824-4839. http://dx.doi.org/10.1175/JCLI3532.1

125. McAfee, S.A., 2014: Consistency and the lack thereof in Pacific Decadal Oscillation impacts on North American winter climate. *Journal of Climate*, **27**, 7410-7431. http://dx.doi.org/10.1175/JCLI-D-14-00143.1

126. Wang, T., O.H. Otterå, Y. Gao, and H. Wang, 2012: The response of the North Pacific Decadal Variability to strong tropical volcanic eruptions. *Climate Dynamics*, **39**, 2917-2936. http://dx.doi.org/10.1007/s00382-012-1373-5

127. Boo, K.-O., B.B.B. Booth, Y.-H. Byun, J. Lee, C. Cho, S. Shim, and K.-T. Kim, 2015: Influence of aerosols in multidecadal SST variability simulations over the North Pacific. *Journal of Geophysical Research Atmospheres*, **120**, 517-531. http://dx.doi.org/10.1002/2014JD021933

128. Yeh, S.-W., W.-M. Kim, Y.H. Kim, B.-K. Moon, R.J. Park, and C.-K. Song, 2013: Changes in the variability of the North Pacific sea surface temperature caused by direct sulfate aerosol forcing in China in a coupled general circulation model. *Journal of Geophysical Research Atmospheres*, **118**, 1261-1270. http://dx.doi.org/10.1029/2012JD017947

129. Meehl, G.A., A. Hu, J.M. Arblaster, J. Fasullo, and K.E. Trenberth, 2013: Externally forced and internally generated decadal climate variability associated with the Interdecadal Pacific Oscillation. *Journal of Climate*, **26**, 7298-7310. http://dx.doi.org/10.1175/JCLI-D-12-00548.1

130. Meehl, G.A., A. Hu, B.D. Santer, and S.-P. Xie, 2016: Contribution of the Interdecadal Pacific Oscillation to twentieth-century global surface temperature trends. *Nature Climate Change*, **6**, 1005-1008. http://dx.doi.org/10.1038/nclimate3107

131. Lapp, S.L., J.-M. St. Jacques, E.M. Barrow, and D.J. Sauchyn, 2012: GCM projections for the Pacific Decadal Oscillation under greenhouse forcing for the early 21st century. *International Journal of Climatology*, **32**, 1423-1442. http://dx.doi.org/10.1002/joc.2364

132. Newman, M., 2007: Interannual to decadal predictability of tropical and North Pacific sea surface temperatures. *Journal of Climate*, **20**, 2333-2356. http://dx.doi.org/10.1175/jcli4165.1

133. Feng, S., Q. Hu, and R.J. Oglesby, 2011: Influence of Atlantic sea surface temperatures on persistent drought in North America. *Climate Dynamics*, **37**, 569-586. http://dx.doi.org/10.1007/s00382-010-0835-x

134. Kavvada, A., A. Ruiz-Barradas, and S. Nigam, 2013: AMO's structure and climate footprint in observations and IPCC AR5 climate simulations. *Climate Dynamics*, **41**, 1345-1364. http://dx.doi.org/10.1007/s00382-013-1712-1

135. Seager, R., Y. Kushnir, M. Ting, M. Cane, N. Naik, and J. Miller, 2008: Would advance knowledge of 1930s SSTs have allowed prediction of the Dust Bowl drought? *Journal of Climate*, **21**, 3261-3281. http://dx.doi.org/10.1175/2007JCLI2134.1

136. Chylek, P. and G. Lesins, 2008: Multidecadal variability of Atlantic hurricane activity: 1851–2007. *Journal of Geophysical Research*, **113**, D22106. http://dx.doi.org/10.1029/2008JD010036

137. Gray, W.M., J.D. Sheaffer, and C.W. Landsea, 1997: Climate trends associated with multidecadal variability of Atlantic hurricane activity. *Hurricanes: Climate and Socioeconomic Impacts*. Diaz, H.F. and R.S. Pulwarty, Eds. Springer, Berlin, Heidelberg, 15-53. http://dx.doi.org/10.1007/978-3-642-60672-4_2

138. Kossin, J.P., 2017: Hurricane intensification along U. S. coast suppressed during active hurricane periods. *Nature*, **541**, 390-393. http://dx.doi.org/10.1038/nature20783

139. Landsea, C.W., R.A. Pielke Jr., A.M. Mestas-Nuñez, and J.A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change*, **42**, 89-129. http://dx.doi.org/10.1023/a:1005416332322

140. Zhang, R. and T.L. Delworth, 2009: A new method for attributing climate variations over the Atlantic hurricane basin's main development region. *Geophysical Research Letters*, **36**, L06701. http://dx.doi.org/10.1029/2009GL037260

141. Caron, L.-P., M. Boudreault, and C.L. Bruyère, 2015: Changes in large-scale controls of Atlantic tropical cyclone activity with the phases of the Atlantic Multidecadal Oscillation. *Climate Dynamics*, **44**, 1801-1821. http://dx.doi.org/10.1007/s00382-014-2186-5

142. Delworth, L.T. and E.M. Mann, 2000: Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dynamics*, **16**, 661-676. http://dx.doi.org/10.1007/s003820000075

143. Delworth, T.L., F. Zeng, L. Zhang, R. Zhang, G.A. Vecchi, and X. Yang, 2017: The central role of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical component of the Atlantic Multidecadal Oscillation. *Journal of Climate*, **30**, 3789-3805. http://dx.doi.org/10.1175/jcli-d-16-0358.1

144. Frankcombe, L.M., A.v.d. Heydt, and H.A. Dijkstra, 2010: North Atlantic multidecadal climate variability: An investigation of dominant time scales and processes. *Journal of Climate*, **23**, 3626-3638. http://dx.doi.org/10.1175/2010jcli3471.1

145. Knight, J.R., C.K. Folland, and A.A. Scaife, 2006: Climate impacts of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, **33**, L17706. http://dx.doi.org/10.1029/2006GL026242

146. Mann, M.E., B.A. Steinman, and S.K. Miller, 2014: On forced temperature changes, internal variability, and the AMO. *Geophysical Research Letters*, **41**, 3211-3219. http://dx.doi.org/10.1002/2014GL059233

147. Moore, G.W.K., J. Halfar, H. Majeed, W. Adey, and A. Kronz, 2017: Amplification of the Atlantic Multidecadal Oscillation associated with the onset of the industrial-era warming. *Scientific Reports*, **7**, 40861. http://dx.doi.org/10.1038/srep40861

148. Terray, L., 2012: Evidence for multiple drivers of North Atlantic multi-decadal climate variability. *Geophysical Research Letters*, **39**, L19712. http://dx.doi.org/10.1029/2012GL053046

149. Miles, M.W., D.V. Divine, T. Furevik, E. Jansen, M. Moros, and A.E.J. Ogilvie, 2014: A signal of persistent Atlantic multidecadal variability in Arctic sea ice. *Geophysical Research Letters*, **41**, 463-469. http://dx.doi.org/10.1002/2013GL058084

150. Trenary, L. and T. DelSole, 2016: Does the Atlantic Multidecadal Oscillation get its predictability from the Atlantic Meridional Overturning Circulation? *Journal of Climate*, **29**, 5267-5280. http://dx.doi.org/10.1175/jcli-d-16-0030.1

FHWA001653

151. Clement, A., K. Bellomo, L.N. Murphy, M.A. Cane, T. Mauritsen, G. Rädel, and B. Stevens, 2015: The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*, **350**, 320-324. http://dx.doi.org/10.1126/science.aab3980

152. Clement, A., M.A. Cane, L.N. Murphy, K. Bellomo, T. Mauritsen, and B. Stevens, 2016: Response to Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation". *Science*, **352**, 1527-1527. http://dx.doi.org/10.1126/science.aaf2575

153. Srivastava, A. and T. DelSole, 2017: Decadal predictability without ocean dynamics. *Proceedings of the National Academy of Sciences*, **114**, 2177-2182. http://dx.doi.org/10.1073/pnas.1614085114

154. Zhang, R., R. Sutton, G. Danabasoglu, T.L. Delworth, W.M. Kim, J. Robson, and S.G. Yeager, 2016: Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation". *Science*, **352**, 1527-1527. http://dx.doi.org/10.1126/science.aaf1660

155. Canty, T., N.R. Mascioli, M.D. Smarte, and R.J. Salawitch, 2013: An empirical model of global climate – Part 1: A critical evaluation of volcanic cooling. *Atmospheric Chemistry and Physics*, **13**, 3997-4031. http://dx.doi.org/10.5194/acp-13-3997-2013

156. Evan, A.T., 2012: Atlantic hurricane activity following two major volcanic eruptions. *Journal of Geophysical Research*, **117**, D06101. http://dx.doi.org/10.1029/2011JD016716

157. Evan, A.T., D.J. Vimont, A.K. Heidinger, J.P. Kossin, and R. Bennartz, 2009: The role of aerosols in the evolution of tropical North Atlantic Ocean temperature anomalies. *Science*, **324**, 778-781. http://dx.doi.org/10.1126/science.1167404

158. Booth, B.B.B., N.J. Dunstone, P.R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, **484**, 228-232. http://dx.doi.org/10.1038/nature10946

159. Dunstone, N.J., D.M. Smith, B.B.B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic aerosol forcing of Atlantic tropical storms. *Nature Geoscience*, **6**, 534-539. http://dx.doi.org/10.1038/ngeo1854

160. Mann, M.E. and K.A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos, Transactions, American Geophysical Union*, **87**, 233-244. http://dx.doi.org/10.1029/2006EO240001

161. Sobel, A.H., S.J. Camargo, T.M. Hall, C.-Y. Lee, M.K. Tippett, and A.A. Wing, 2016: Human influence on tropical cyclone intensity. *Science*, **353**, 242-246. http://dx.doi.org/10.1126/science.aaf6574

162. Carslaw, K.S., L.A. Lee, C.L. Reddington, K.J. Pringle, A. Rap, P.M. Forster, G.W. Mann, D.V. Spracklen, M.T. Woodhouse, L.A. Regayre, and J.R. Pierce, 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, **503**, 67-71. http://dx.doi.org/10.1038/nature12674

163. Stevens, B., 2015: Rethinking the lower bound on aerosol radiative forcing. *Journal of Climate*, **28**, 4794-4819. http://dx.doi.org/10.1175/jcli-d-14-00656.1

164. Ting, M., Y. Kushnir, R. Seager, and C. Li, 2009: Forced and internal twentieth-century SST trends in the North Atlantic. *Journal of Climate*, **22**, 1469-1481. http://dx.doi.org/10.1175/2008jcli2561.1

165. Tung, K.-K. and J. Zhou, 2013: Using data to attribute episodes of warming and cooling in instrumental records. *Proceedings of the National Academy of Sciences*, **110**, 2058-2063. http://dx.doi.org/10.1073/pnas.1212471110

166. Zhang, R., T.L. Delworth, R. Sutton, D.L.R. Hodson, K.W. Dixon, I.M. Held, Y. Kushnir, J. Marshall, Y. Ming, R. Msadek, J. Robson, A.J. Rosati, M. Ting, and G.A. Vecchi, 2013: Have aerosols caused the observed Atlantic multidecadal variability? *Journal of the Atmospheric Sciences*, **70**, 1135-1144. http://dx.doi.org/10.1175/jas-d-12-0331.1

167. Vincze, M. and I.M. Jánosi, 2011: Is the Atlantic Multidecadal Oscillation (AMO) a statistical phantom? *Nonlinear Processes in Geophysics*, **18**, 469-475. http://dx.doi.org/10.5194/npg-18-469-2011

168. Dima, M. and G. Lohmann, 2007: A hemispheric mechanism for the Atlantic Multidecadal Oscillation. *Journal of Climate*, **20**, 2706-2719. http://dx.doi.org/10.1175/jcli4174.1

169. Chylek, P., C.K. Folland, H.A. Dijkstra, G. Lesins, and M.K. Dubey, 2011: Ice-core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, **38**, L13704. http://dx.doi.org/10.1029/2011GL047501

170. Gray, S.T., L.J. Graumlich, J.L. Betancourt, and G.T. Pederson, 2004: A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical Research Letters*, **31**, L12205. http://dx.doi.org/10.1029/2004GL019932

FHWA001654

171. Knudsen, M.F., B.H. Jacobsen, M.-S. Seidenkrantz, and J. Olsen, 2014: Evidence for external forcing of the Atlantic Multidecadal Oscillation since termination of the Little Ice Age. *Nature Communications*, **5**, 3323. http://dx.doi.org/10.1038/ncomms4323

172. Mann, M.E., J.D. Woodruff, J.P. Donnelly, and Z. Zhang, 2009: Atlantic hurricanes and climate over the past 1,500 years. *Nature*, **460**, 880-883. http://dx.doi.org/10.1038/nature08219

173. Deser, C., A.S. Phillips, M.A. Alexander, and B.V. Smoliak, 2014: Projecting North American climate over the next 50 years: Uncertainty due to internal variability. *Journal of Climate*, **27**, 2271-2296. http://dx.doi.org/10.1175/JCLI-D-13-00451.1

174. Wettstein, J.J. and C. Deser, 2014: Internal variability in projections of twenty-first-century Arctic sea ice loss: Role of the large-scale atmospheric circulation. *Journal of Climate*, **27**, 527-550. http://dx.doi.org/10.1175/JCLI-D-12-00839.1

175. Thompson, D.W.J., E.A. Barnes, C. Deser, W.E. Foust, and A.S. Phillips, 2015: Quantifying the role of internal climate variability in future climate trends. *Journal of Climate*, **28**, 6443-6456. http://dx.doi.org/10.1175/JCLI-D-14-00830.1

176. Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*, **26**, 8709-8743. http://dx.doi.org/10.1175/JCLI-D-12-00567.1

177. NWS, 2016: Global Circulations in NWS Jet Stream: An Online School for Weather. National Weather Service. http://www.srh.noaa.gov/jetstream/global/circ.html

178. Lindsey, R., 2016: How El Niño and La Niña affect the winter jet stream and U.S. climate. Climate.gov. https://www.climate.gov/news-features/featured-images/how-el-ni%C3%B1o-and-la-ni%C3%B1a-affect-winter-jet-stream-and-us-climate

179. Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K. Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53**, 1232-1251. http://dx.doi.org/10.1175/JAMC-D-13-0248.1

6 Temperature Changes in the United States

KEY FINDINGS

1. Annual average temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear regression for the period 1895–2016 (*very high confidence*). Surface and satellite data are consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*).

2. There have been marked changes in temperature extremes across the contiguous United States. The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s. The Dust Bowl era of the 1930s remains the peak period for extreme heat. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*)

3. Annual average temperature over the contiguous United States is projected to rise (*very high confidence*). Increases of about 2.5°F (1.4°C) are projected for the period 2021–2050 relative to 1976–2005 in all RCP scenarios, implying recent record-setting years may be “common” in the next few decades (*high confidence*). Much larger rises are projected by late century (2071–2100): 2.8°–7.3°F (1.6°–4.1°C) in a lower scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in the higher scenario (RCP8.5) (*high confidence*).

4. Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both expected to increase. Cold waves are projected to become less intense while heat waves will become more intense. The number of days below freezing is projected to decline while the number above 90°F will rise. (*Very high confidence*)

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Introduction

Temperature is among the most important climatic elements used in decision-making. For example, builders and insurers use temperature data for planning and risk management while energy companies and regulators use temperature data to predict demand and set utility rates. Temperature is also a key indicator of climate change: recent increases are apparent over the land, ocean, and troposphere, and substantial changes are expected for this century. This chapter summarizes the major observed and projected changes in near-surface air temperature over the United States, emphasizing new data sets and model projections since the Third National Climate Assessment (NCA3). Changes are depicted using a spectrum of observations, including surface weather stations, moored ocean buoys, polar-orbiting satellites, and temperature-sensitive proxies. Projections are based on global models and downscaled products from CMIP5 (Coupled Model Intercomparison Project Phase 5) using a suite of Representative Concentration Pathways (RCPs; see Ch. 4: Projections for more on RCPs and future scenarios).

6.1 Historical Changes

6.1.1 Average Temperatures

Changes in average temperature are described using a suite of observational datasets. As in NCA3, changes in land temperature are assessed using the nClimGrid dataset.[1, 2] Along U.S. coastlines, changes in sea surface temperatures are quantified using a new reconstruction[3] that forms the ocean component of the NOAA Global Temperature dataset.[4] Changes in middle tropospheric temperature are examined using updated versions of multiple satellite datasets.[5, 6, 7]

The annual average temperature of the contiguous United States has risen since the start of the 20th century. In general, temperature increased until about 1940, decreased until about 1970, and increased rapidly through 2016. Because the increase was not constant over time, multiple methods were evaluated in this report (as in NCA3) to quantify the trend. All methods yielded rates of warming that were significant at the 95% level. The lowest estimate of 1.2°F (0.7°C) was obtained by computing the difference between the average for 1986–2016 (i.e., present-day) and the average for 1901–1960 (i.e., the first half of the last century). The highest estimate of 1.8°F (1.0°C) was obtained by fitting a linear (least-squares) regression line through the period 1895–2016. Thus, the temperature increase cited in this assessment is 1.2°–1.8°F (0.7°–1.0°C).

This increase is about 0.1°F (0.06°C) less than presented in NCA3, and it results from the use of slightly different periods in each report. In particular, the decline in the lower bound stems from the use of different time periods to represent present-day climate (NCA3 used 1991–2012, which was slightly warmer than the 1986–2016 period used here). The decline in the upper bound stems mainly from temperature differences late in the record (e.g., the last year of data available for NCA3 was 2012, which was the warmest year on record for the contiguous United States).

Each NCA region experienced a net warming through 2016 (Table 6.1). The largest changes were in the western United States, where average temperature increased by more than 1.5°F (0.8°C) in Alaska, the Northwest, the Southwest, and also in the Northern Great Plains. As noted in NCA3, the Southeast had the least warming, driven by a combination of natural variations and human influences.[8] In most regions, average minimum temperature increased at a slightly higher rate than average maximum temperature, with the Midwest having the largest discrepancy, and the Southwest and Northwest having the smallest. This differential rate of warming resulted in a continuing

Table 6.1. Observed changes in annual average temperature (°F) for each National Climate Assessment region. Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska, Hawai'i, and the Caribbean). Estimates are derived from the nClimDiv dataset[1,2].

NCA Region	Change in Annual Average Temperature	Change in Annual Average Maximum Temperature	Change in Annual Average Minimum Temperature
Contiguous U.S.	1.23°F	1.06°F	1.41°F
Northeast	1.43°F	1.16°F	1.70°F
Southeast	0.46°F	0.16°F	0.76°F
Midwest	1.26°F	0.77°F	1.75°F
Great Plains North	1.69°F	1.66°F	1.72°F
Great Plains South	0.76°F	0.56°F	0.96°F
Southwest	1.61°F	1.61°F	1.61°F
Northwest	1.54°F	1.52°F	1.56°F
Alaska	1.67°F	1.43°F	1.91°F
Hawaii	1.26°F	1.01°F	1.49°F
Caribbean	1.35°F	1.08°F	1.60°F

decrease in the diurnal temperature range that is consistent with other parts of the globe.[9] Annual average sea surface temperature also increased along all regional coastlines (see Figure 1.3), though changes were generally smaller than over land owing to the higher heat capacity of water. Increases were largest in Alaska (greater than 1.0°F [0.6°C]) while increases were smallest (less than 0.5°F [0.3°C]) in coastal areas of the Southeast.

More than 95% of the land surface of the contiguous United States had an increase in annual average temperature (Figure 6.1). In contrast, only small (and somewhat dispersed) parts of the Southeast and Southern Great Plains experienced cooling. From a seasonal perspective, warming was greatest and most widespread in winter, with increases of over 1.5°F (0.8°C) in most areas. In summer, warming was less extensive (mainly along the East Coast and in the western third of the Nation), while cooling was evident in parts of the Southeast, Midwest, and Great Plains.

There has been a rapid increase in the average temperature of the contiguous United States over the past several decades. There is general consistency on this point between the surface thermometer record from NOAA[1] and the middle tropospheric satellite records from Remote Sensing Systems (RSS),[5] NOAA's Center for Satellite Applications and Research (STAR),[7] and the University of Alabama in Huntsville (UAH).[6] In particular, for the period 1979–2016, the rate of warming in the surface record was 0.512°F (0.284°C) per decade, versus trends of 0.455°F (0.253°C), 0.421°F (0.234°C), and 0.289°F (0.160 °C) per decade for RSS version 4, STAR version 3, and UAH version 6, respectively (after accounting for stratospheric influences). All trends are statistically significant at the 95% level. For the contiguous United States, the year 2016 was the second-warmest on record at the surface and in the middle troposphere (2012 was the warmest year at the surface, and 2015 was the warmest in the middle troposphere). Generally speaking, surface and satellite records

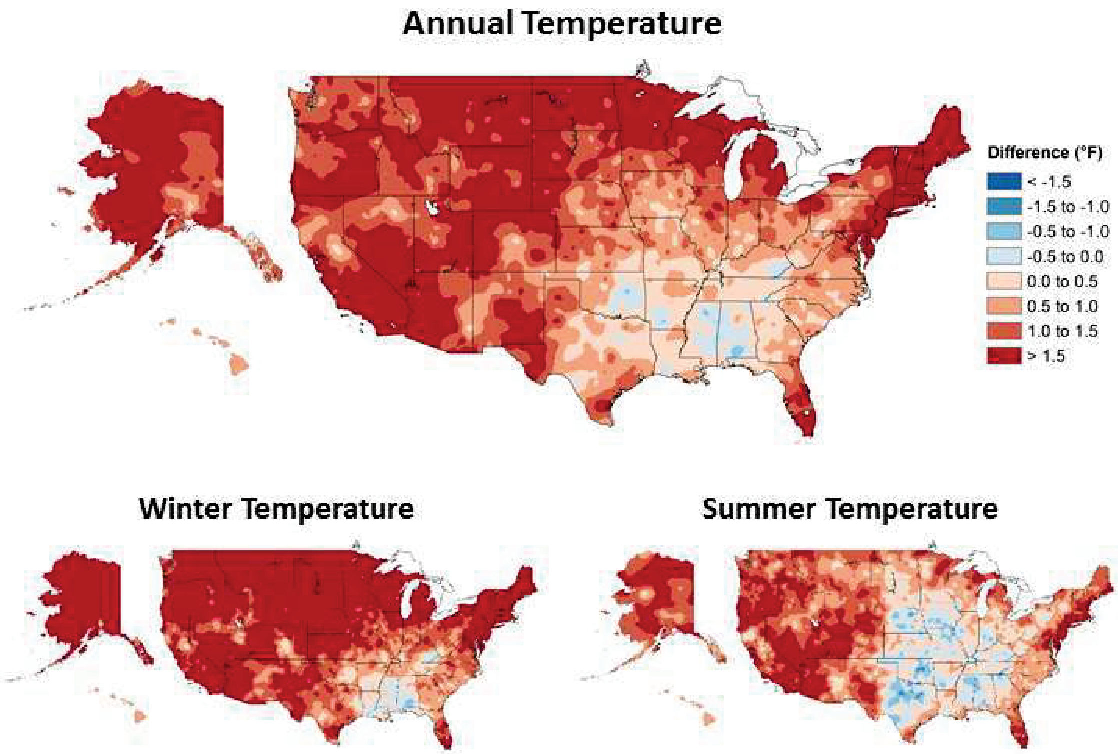

Figure 6.1. Observed changes in annual, winter, and summer temperature (°F). Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawai'i). Estimates are derived from the nClimDiv dataset.[1, 2] (Figure source: NOAA/NCEI).

do not have identical trends because they do not represent the same physical quantity; surface measurements are made using thermometers in shelters about 1.5 meters above the ground whereas satellite measurements are mass-weighted averages of microwave emissions from deep atmospheric layers. The UAH record likely has a lower trend because it differs from the other satellite products in the treatment of target temperatures from the NOAA-9 satellite as well as in the correction for diurnal drift.[10]

Recent paleo-temperature evidence confirms the unusual character of wide-scale warming during the past few decades as determined from the instrumental record. The most important new paleoclimate study since NCA3 showed that for each of the seven continental regions, the reconstructed area-weighted average temperature for 1971–2000 was higher than for any other time in nearly 1,400 years,[11] although with significant uncertainty around the central estimate that leads to this conclusion. Recent (up to 2006) 30-year smoothed temperatures across temperate North America (including most of the continental United States) are similarly reconstructed as the warmest over the past 1,500 years[12] (Figure 6.2). Unlike the PAGES 2k seven-continent result mentioned above, this conclusion for North America is robust in relation to the estimated uncertainty range. Reconstruction data since 1500 for western temperate North America show the same conclusion at the annual time scale for 1986–2005. This time period and the running 20-year periods thereafter are warmer than all possible continuous 20-year sequences in a 1,000-member statistical reconstruction ensemble.[13]

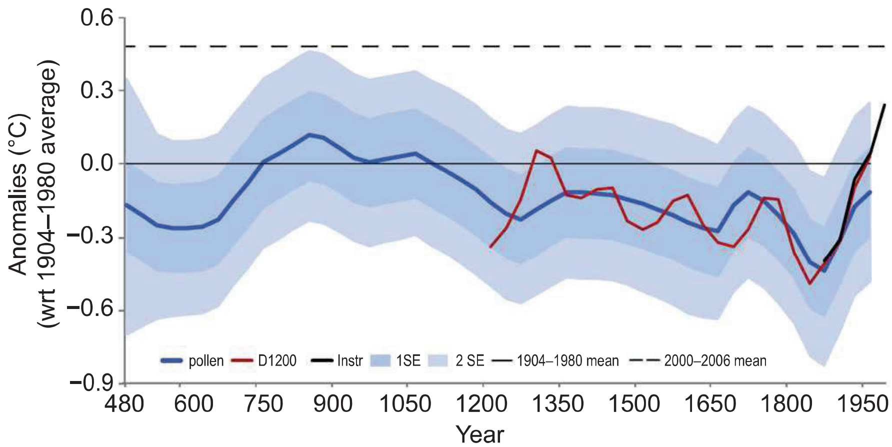

Figure 6.2. Pollen-based temperature reconstruction for temperate North America. The blue curve depicts the pollen-based reconstruction of 30-year averages (as anomalies from 1904 to 1980) for the temperate region (30°–55°N, 75°–130°W). The red curve shows the corresponding tree ring-based decadal average reconstruction, which was smoothed and used to calibrate the lower-frequency pollen-based estimate. Light (medium) blue zones indicate 2 standard error (1 standard error) uncertainty estimations associated with each 30-year value. The black curve shows comparably smoothed instrumental temperature values up to 1980. The dashed black line represents the average temperature anomaly of comparably smoothed instrumental data for the period 2000–2006. (Figure source: NOAA NCEI).

6.1.2 Temperature Extremes

Shifts in temperature extremes are examined using a suite of societally relevant climate change indices[14, 15] derived from long-term observations of daily surface temperature.[16] The coldest and warmest temperatures of the year are of particular relevance given their widespread use in engineering, agricultural, and other sectoral applications (for example, extreme annual design conditions by the American Society of Heating, Refrigeration, and Air Conditioning; plant hardiness zones by the U.S. Department of Agriculture). Cold waves and heat waves (that is, extended periods of below or above normal temperature) are likewise of great importance because of their numerous societal and environmental impacts, which span from human health to plant and animal phenology. Changes are considered for a spectrum of event frequencies and intensities, ranging from the typical annual extreme to the 1-in-10 year event (an extreme that only has a 10% chance of occurrence in any given year). The discussion focuses on the contiguous United States; Alaska, Hawai'i, and the Caribbean do not have a sufficient number of long-term stations for a century-scale analysis.

Cold extremes have become less severe over the past century. For example, the coldest daily temperature of the year has increased at most locations in the contiguous United States (Figure 6.3). All regions experienced net increases (Table 6.2), with the largest rises in the Northern Great Plains and the Northwest (roughly 4.5°F [2.5°C]), and the smallest in the Southeast (about 1.0°F [0.6°C]). In general, there were increases throughout the record, with a slight acceleration in recent decades (Figure 6.3). The temperature of extremely cold days (1-in-10 year events) generally exhibited the same pattern of increases as the coldest daily temperature of the year. Consistent with these increases, the number of cool nights per year (those with a minimum temperature below the 10th percentile for 1961–1990) declined in all regions, with much of the West having decreases of roughly two weeks. The frequency of cold waves (6-day periods with a minimum temperature below the

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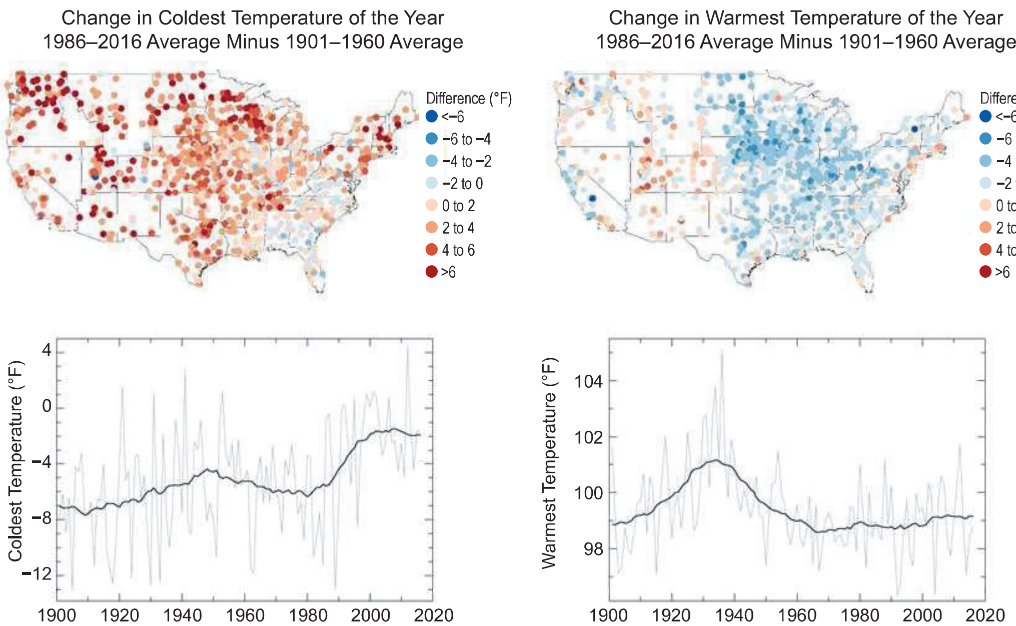

Figure 6.3. Observed changes in the coldest and warmest daily temperatures (°F) of the year in the contiguous United States. Maps (top) depict changes at stations; changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Time series (bottom) depict the area-weighted average for the contiguous United States. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

Table 6.2. Observed changes in the coldest and warmest daily temperatures (°F) of the year for each National Climate Assessment region in the contiguous United States. Changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16]

NCA Region	Change in Coldest Day of the Year	Change in Warmest Day of the Year
Northeast	2.83°F	−0.92°F
Southeast	1.13°F	−1.49°F
Midwest	2.93°F	−2.22°F
Great Plains North	4.40°F	−1.08°F
Great Plains South	3.25°F	−1.07°F
Southwest	3.99°F	0.50°F
Northwest	4.78°F	−0.17°F

10th percentile for 1961–1990) has fallen over the past century (Figure 6.4). The frequency of intense cold waves (4-day, 1-in-5 year events) peaked in the 1980s and then reached record-low levels in the 2000s.[17]

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime

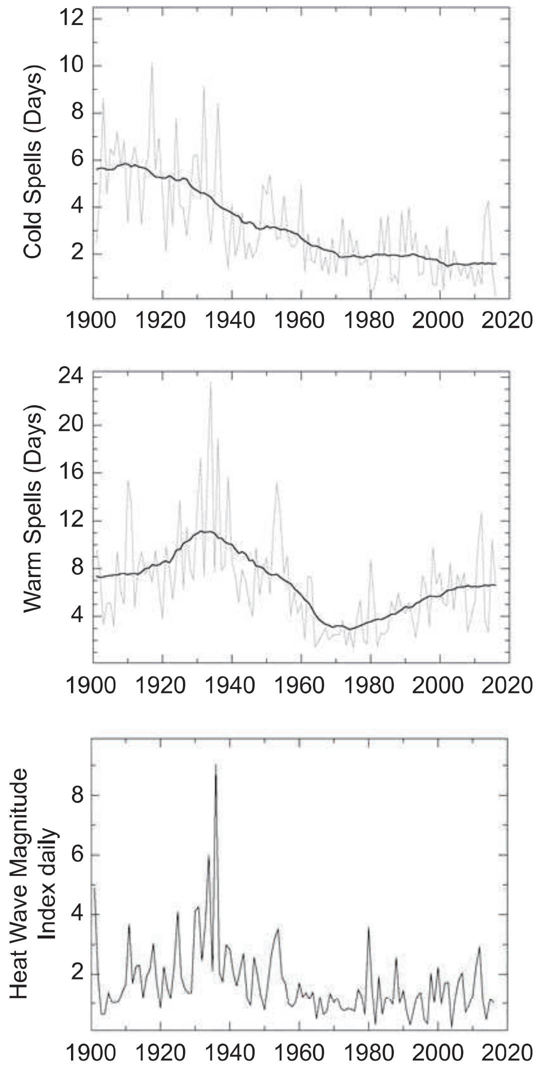

Figure 6.4. Observed changes in cold and heat waves in the contiguous United States. The top panel depicts changes in the frequency of cold waves; the middle panel depicts changes in the frequency of heat waves; and the bottom panel depicts changes in the intensity of heat waves. Cold and heat wave frequency indices are defined in Zhang et al.,[15] and the heat wave intensity index is defined in Russo et al.[14] Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

precipitation deficits and land mismanagement.[18] However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s,[19] and agricultural intensification may have suppressed the hottest extremes in the Midwest.[20] Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s. The frequency of intense heat waves (4-day, 1-in-5 year events) has generally increased since the 1960s in most regions except the Midwest and the Great

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Plains.[17, 21] Since the early 1980s (Figure 6.4), there is suggestive evidence of a slight increase in the intensity of heat waves nationwide[14] as well as an increase in the concurrence of droughts and heat waves.[22]

Changes in the occurrence of record-setting daily temperatures are also apparent. Very generally, the number of record lows has been declining since the late-1970s while the number of record highs has been rising.[23] By extension, there has been an increase in the ratio of the number of record highs to record lows (Figure 6.5). Over the past two decades, the average of this ratio exceeds two (meaning that twice as many high-temperature records have been set as low-temperature records). The number of new highs has surpassed the number of new lows in 15 of the last 20 years, with 2012 and 2016 being particularly extreme (ratios of seven and five, respectively).

6.2 Detection and Attribution

6.2.1 Average Temperatures

While a confident attribution of global temperature increases to anthropogenic forcing has been made,[24] detection and attribution assessment statements for smaller regions are generally much weaker. Nevertheless, some detectable anthropogenic influences on average temperature have been reported for North America and parts of the United States (e.g., Christidis et al. 2010;[25] Bonfils et al. 2008;[26] Pierce et al. 2009[27]). Figure 6.6 shows an example for linear trends for 1901–2015, indicating a detectable anthropogenic warming since 1901 over the western and northern regions of the contiguous United States for the CMIP5 multimodel ensemble—a condition that was also met for most of the individual models.[28] The Southeast stands out as the only region with no "detectable" warming since 1901; observed trends there were inconsistent with CMIP5 All Forcing historical runs.[28] The cause

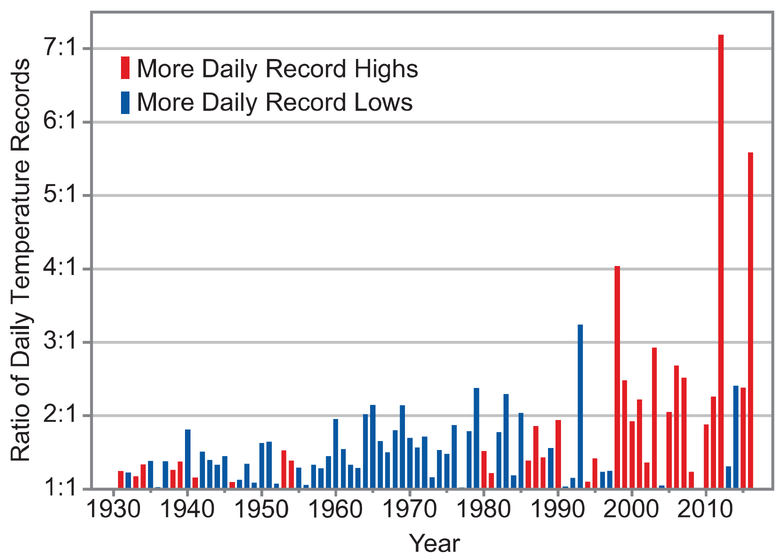

Figure 6.5. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

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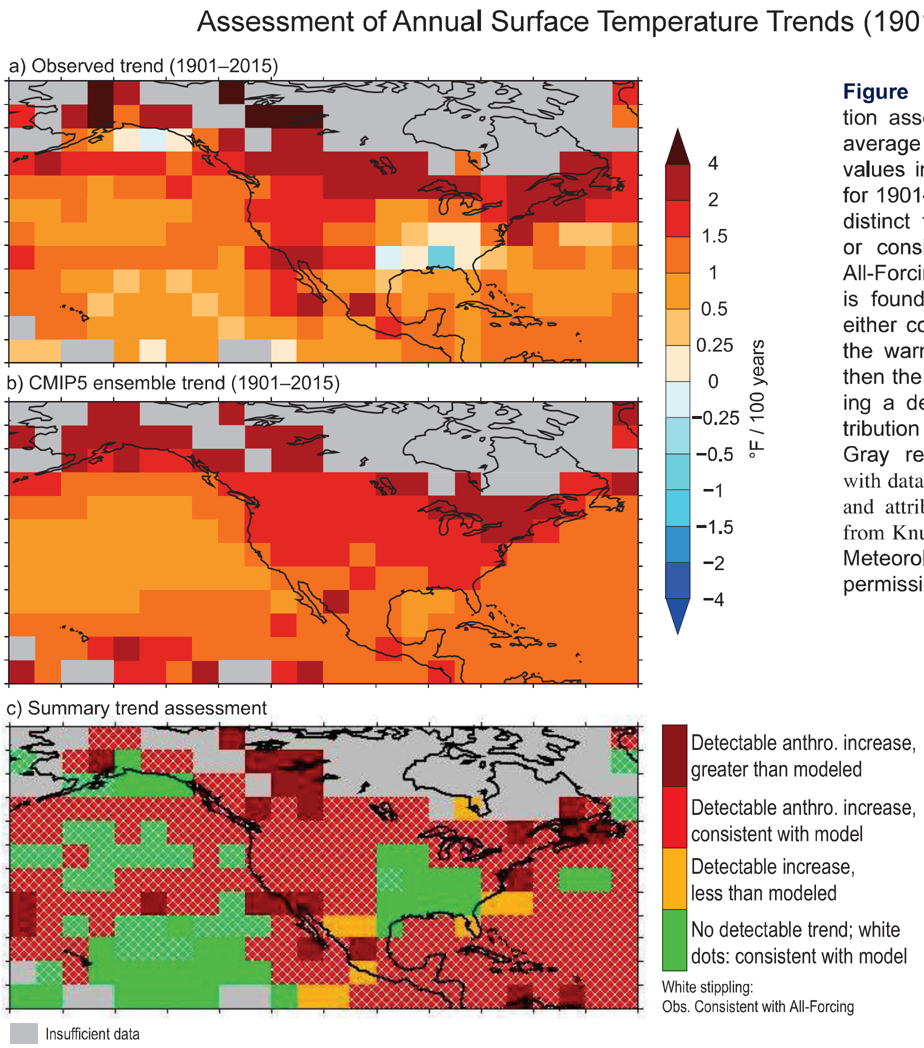

Figure 6.6. Detection and attribution assessment of trends in annual average temperature (°F). Grid-box values indicate whether linear trends for 1901–2015 are detectable (that is, distinct from natural variability) and/or consistent with CMIP5 historical All-Forcing runs. If the grid-box trend is found to be both detectable and either consistent with or greater than the warming in the All-Forcing runs, then the grid box is assessed as having a detectable anthropogenic contribution to warming over the period. Gray regions represent grid boxes with data that are too sparse for detection and attribution. (Figure source: updated from Knutson et al. 2013;[28] © American Meteorological Society. Used with permission.)

of this "warming hole," or lack of a long-term warming trend, remains uncertain, though it is likely a combination of natural and human causes. Some studies conclude that changes in anthropogenic aerosols have played a crucial role (e.g., Leibensperger et al. 2012;[29, 30] Yu et al. 2014[31]), whereas other studies infer a possible large role for atmospheric circulation,[32] internal climate variability (e.g., Meehl et al. 2012;[8] Knutson et al. 2013[28]), and changes in land use (e.g., Goldstein et al. 2009;[33] Xu et al. 2015[34]). Notably, the Southeast has been warming rapidly since the early 1960s.[35, 36] In summary, there is medium confidence for detectable anthropogenic warming over the western and northern regions of the contiguous United States.

6.2.2 Temperature Extremes

The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5)[24] concluded that it is very likely that human influence has contributed to the observed changes in frequency and intensity of temperature extremes on the global scale since the mid-20th century. The combined influence of anthropogenic and natural forcings was also detectable (medium confidence) over large subregions of North America (e.g., Zwiers et al. 2011;[37] Min et al. 2013[38]). In general, however, results for the contiguous United States are not as compelling as for global land areas, in part because detection of changes in U.S. regional temperature extremes is affected by

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extreme temperature in the 1930s.[17] Table 6.3 summarizes available attribution statements for recent extreme U.S. temperature events. As an example, the recent record or near-record high March–May average temperatures occurring in 2012 over the eastern United States were attributed in part to external (natural plus anthropogenic) forcing;[39] the century-scale trend response of temperature to external forcing is typically a close approximation to the anthropogenic forcing response alone. Another study found that although the extreme March 2012 warm anomalies over the United States were mostly due to natural variability, anthropogenic warming contributed to the severity.[40] Such statements reveal that both natural and anthropogenic factors influence the severity of extreme temperature events. Nearly every modern analysis of current extreme hot and cold events reveals some degree of attributable human influence.

6.3 Projected Changes

6.3.1 Average Temperatures

Temperature projections are based on global model results and associated downscaled products from CMIP5 using a suite of Representative Concentration Pathways (RCPs). In contrast to NCA3, model weighting is employed to refine projections of temperature for each RCP (Ch. 4: Projections; Appendix B: Model Weighting). Weighting parameters are based on model independence and skill over North America for seasonal temperature and annual extremes. Unless stated otherwise, all changes presented here represent the weighted multimodel mean. The weighting scheme helps refine confidence and likelihood statements, but projections of U.S. surface air temperature remain very similar to those in NCA3. Generally speaking, extreme temperatures are projected to increase even more than average temperatures.[41]

Table 6.3. Extreme temperature events in the United States for which attribution statements have been made. There are three possible attribution statements: "+" shows an attributable human-induced increase in frequency or intensity, "–" shows an attributable human-induced decrease in frequency or intensity, "0" shows no attributable human contribution.

Study	Period	Region	Type	Statement
Rupp et al. 2012[52] Angélil et al. 2017[53]	Spring/Summer 2011	Texas	Hot	+ +
Hoerling et al. 2013[54]	Summer 2011	Texas	Hot	+
Diffenbaugh and Scherer 2013[55] Angélil et al. 2017[53]	July 2012	Northcentral and Northeast	Hot	+ +
Cattiaux and Yiou 2013[56] Angélil et al. 2017[53]	Spring 2012	East	Hot	0 +
Knutson et al. 2013b[39] Angélil et al. 2017[53]	Spring 2012	East	Hot	+ +
Jeon et al 2016[57]	Summer 2011	Texas/ Oklahoma	Hot	+
Dole et al. 2014[40]	March 2012	Upper Midwest	Hot	+
Seager et al. 2014[58]	2011–2014	California	Hot	+
Wolter et al. 2015[59]	Winter 2014	Midwest	Cold	–
Trenary et al. 2015[60]	Winter 2014	East	Cold	0

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The annual average temperature of the contiguous United States is projected to rise throughout the century. Increases for the period 2021–2050 relative to 1976–2005 are projected to be about 2.5°F (1.4°C) for a lower scenario (RCP4.5) and 2.9°F (1.6°C) for the higher scenario (RCP8.5); the similarity in warming reflects the similarity in greenhouse gas concentrations during this period (Figure 4.1). Notably, a 2.5°F (1.4°C) increase makes the near-term average comparable to the hottest year in the historical record (2012). In other words, recent record-breaking years may be "common" in the next few decades. By late-century (2071–2100), the RCPs diverge significantly, leading to different rates of warming: approximately 5.0°F (2.8°C) for RCP4.5 and 8.7°F (4.8°C) for RCP8.5. Likewise, there are different ranges of warming for each scenario: 2.8°–7.3°F (1.6°–4.1°C) for RCP4.5 and 5.8°–11.9°F (3.2°–6.6°C) for RCP8.5. (The range is defined here as the difference between the average increase in the three coolest models and the average increase in the three warmest models.) For both RCPs, slightly greater increases are projected in summer than winter (except for Alaska), and average maximums will rise slightly faster than average minimums (except in the Southeast and Southern Great Plains).

Statistically significant warming is projected for all parts of the United States throughout the century (Figure 6.7). Consistent with polar amplification, warming rates (and spatial gradients) are greater at higher latitudes. For example, warming is largest in Alaska (more than 12.0°F [6.7°C] in the northern half of the state by late-century under RCP8.5), driven in part by a decrease in snow cover and thus surface albedo. Similarly, northern regions of the contiguous United States have slightly more warming than other regions (roughly 9.0°F [5.5°C] in the Northeast, Midwest, and Northern Great Plains by late-century under RCP8.5; Table 6.4). The Southeast has slightly less warming because of latent heat release from increases in evapotranspiration (as is already evident in the observed record). Warming is smallest in Hawai'i and the Caribbean (roughly 4.0°–6.0°F [2.2°–3.3°C] by late century under RCP8.5) due to the moderating effects of surrounding oceans. From a sub-regional perspective, less warming is projected along the coasts of the contiguous United States, again due to maritime influences, although increases are still substantial. Warming at higher elevations may be underestimated because the resolution of the CMIP5 models does not capture orography in detail.

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